PREPARING FOR A CHANGING CLIMATE

The Potential Consequences of Climate Variability and Change

California

A Report of the California Regional Assessment Group

For the U.S. Global Change Research Program

September 2002

The Potential Consequences of Climate Variability and Change for California

The California Regional Assessment

A Report of the California Regional Assessment Group
For the U.S. Global Change Research Program

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NOTICE

This **DRAFT FINAL REPORT** of the regional assessment is posted for public review and comment. Comments, corrections, and additions are welcome and encouraged.

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The California Regional Assessment

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Preface

This assessment of the potential impacts of climate change and variability is a work in progress. It builds on important scientific research and analysis conducted over the past several decades which provides a valuable basis for the ongoing assessment. In addition to the outstanding university research institutions, national laboratories, and other research centers in the state, federal and state agencies have contributed significantly to our understanding of climate change and related topics.

Everything about California seems to be dynamic, and any attempt to capture its essence will yield only a snapshot that begins to be outdated as soon as it is created. This report has attempted to synthesize and incorporate a large amount of information about the economy, environment, and society that will be affected by climate change. It presents this portrait with what is currently known about the potential impacts of climate change and variability.

Scientists worldwide are constantly advancing our understanding of a changing climate and its possible consequences. In this assessment, numerous scientific studies are referenced to assist the interested reader in digging further into the literature. Wherever possible, web-based information is provided to allow readers to access the vast body of information available.

The information provided here is not intended, however, to be an exhaustive compilation of all climate research, nor is it a comprehensive listing of all the possible consequences of climate change on California. Rather, it is an overview of potential implications of climate change for this important region, and a summary of what may be in store in the next century—based on what we know at this moment in time. These sketches will no doubt change as we learn more about the complicated nature of global climate and of the systems they impact.

I assume full responsibility for any errors or omissions, and I would be grateful for comments, corrections, and additions. Please direct them to me at *wilkinso@lifesci.ucsb.edu*

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Table of Contents

Preface iii

Executive Summary 1

I. The United States Global Change Research Program and the Assessment of Potential Impacts of Climate Change and Variability

Introduction: The U.S. Climate Change Assessment Process 1-1
Key Questions Addressed in the Assessment 1-3
Goals of the Assessment Process 1-3
Climate Observations 1-4
Summary 1-8
Sources 1-9

II. Climate Change Science

Introduction 2-1
The Greenhouse Effect 2-2
Scientific Analysis of Climate Change 2-3
Climate Scenarios 2-6
Global Warming and Rates of Change 2-7
Abrupt Change and "Inevitable Surprises" 2-9
The IPCC Assessment 2-11
Measuring and Reporting Uncertainties 2-12
Modeling Climate Change 2-14
Climate Patterns and Oscillations 2-15
El Niño Southern Oscillation 2-18
Sea Level Change 2-25
Summary 2-27
Sources 2-28

III. The California Region

Introduction: The People and the Place 3-1
The People of California 3-3
California's Geography and Environment 3-9
- Climate Variability in Time and Place in California 3-11
- California's Air Quality 3-15
- Ecosystems Under Stress 3-17

California's Economy 3-17
- California as a "G-7" Country 3-17
- California's Major Economic Sectors 3-18

Industry Highlights 3-19
California's Infrastructure 3-22
Water Systems 3-23
Transportation Systems 3-27
Energy Systems 3-28
California Institutions Addressing Climate Change 3-30
California's Greenhouse Gas Emissions 3-31
Summary 3-34
Sources 3-35

IV. Potential Impacts of Climate Change and Variability for California

Part 1. California's Water Systems and the Potential Impacts of Climate Change and Variability

Introduction 4-1-1
California's Water Systems and Infrastructure 4-1-2
Three Major Sources of Water Supply 4-1-4
A Stressed Water System 4-1-5
Water Use 4-1-6
Surface Water Storage: Dams in California 4-1-13
Water Supply Reductions 4-1-15
Water Supply Additions 4-1-19
Inter-basin Transfers and Major Water Supply Systems in California 4-1-21
The State Water Project 4-1-21
The Central Valley Project 4-1-24
The Colorado River Aqueduct 4-1-26
The Metropolitan Water District 4-1-29
Local Water Sources in Southern California 4-1-30
Elements of Water Supply Systems 4-1-31
Treatment and Distribution 4-1-31
Water Catchment and Treatment 4-1-32
Potential Impacts of Climate Change on Water Systems in California 4-1-33
Climate Trends in California 4-1-35
Temperature Trends in California 4-1-35
Precipitation Trends in California 4-1-36
Runoff Trends in California 4-1-40
Drought Trends in California 4-1-44
The Paleoclimate Record 4-1-48
Modeling Climate Change and Water 4-1-49
Canadian and Hadley GCMs and the National Assessment 4-1-51
Downscaling Climate Models for California 4-1-53
Evaporation and Transpiration 4-1-57
Snowpack 4-1-62
Runoff 4-1-69
Water Quality 4-1-74
Variability and Extreme Events 4-1-76
Floods 4-1-77
Climate Patterns and Oscillations 4-1-79
Lake Levels and Conditions 4-1-85

Groundwater 4-1-85
Sea Level 4-1-86
Direct Effects on Ecosystems 4-1-90
Medium Range Forecasts 4-1-91
Using Science for Adaptive Management: CALFED 4-1-96
Summary 4-1-101
Sources 4-1-103

Part 2. Natural Resource Systems, Ecological Systems, and the Potential Impacts of Climate Change and Variability

Introduction 4-2-1
Ecosystems and Climate 4-2-2
Ecosystem Services 4-2-4
Summary of Potential Impacts 4-2-6
Potential Shifts in Ecosystems Based on Modeling Results 4-2-8
Biodiversity and Climate Change 4-2-11
Threatened and Endangered Species 4-2-12
Habitat Loss 4-2-13
Invasive Species 4-2-13
Climate Change, Natural Systems, and Fire 4-2-14
Water and Ecosystems 4-2-22
Freshwater Ecosystems 4-2-23
Fisheries 4-2-25
Marine and Related Coastal Ecosystems 4-2-25
Marine Ecosystem Benefits 4-2-26
Stresses affecting the region, its natural resources, and economic sectors 4-2-28
How climate variability/change might amplify or dampen stresses 4-2-29
New Information 4-2-29
Win-Win Coping Strategies 4-2-30
The California Current and Ecosystem Change 4-2-30
Oscillations 4-2-31
Sea Level Rise and Ecosystems 4-2-32
Climate Change and Growth Rates of Vegetation 4-2-34
Pests 4-2-34
Fog Regimes 4-2-35
Desert Ecosystems 4-2-36
Ecological Surprises 4-2-38
Summary 4-2-39
Sources 4-2-40

Part 3. California's Economy, Society, and Infrastructure and the Potential Impacts of Climate Change and Variability

Introduction 4-3-1
Infrastructure and Economic Sectors 4-3-1
Social Equity Considerations 4-3-2
Fire Risk and Climate Change 4-3-2
Coastal Impacts on Structures and Infrastructure 4-3-4
Economic Impacts on Coastal Resources and Systems 4-3-7
Potential Impacts of Sea Level Rise 4-3-8
El Niño and Storm Surge Impacts 4-3-9

Impacts of Sea Level Rise on Coastal Aquifers 4-3-10
Fisheries 4-3-13
Floods and Landslides 4-3-18
Agriculture 4-3-19
Diversity of Agricultural Production 4-3-20
Some Climate Impacts May be Subtle 4-3-21
Carbon Dioxide Fertilization 4-3-22
Agriculture and Potential Impacts on Water Systems 4-3-23
Potential Benefits of Climate Change for Agriculture 4-3-24
Forestry 4-3-26
Energy Supply Systems 4-3-28
Transmission Systems 4-3-29
Hydropower 4-3-31
Natural Gas Infrastructure 4-3-33
Petroleum Production and Distribution 4-3-34
Wind Energy 4-3-35
Energy Use 4-3-36
Mining, Oil, and Gas 4-3-36
Summary 4-3-37
Sources 4-3-39

Part 4. Potential Impacts of Climate Change and Variability on Human Health
Key Findings Regarding Potential Health Impacts 4-4-1
Potential Direct and Indirect Impacts on Human Health 4-4-5
Temperature 4-4-5
Air Quality Impacts 4-4-8
Vector-Borne Diseases 4-4-9
Climate Change and Valley Fever 4-4-10
Hantavirus 4-4-12
Encephalitides 4-4-14
Summary 4-4-15
Sources 4-4-17

V. Response Strategies: Coping and Adaptation

Developing Informed and Systematic Response Strategies 5-1
A Systematic Approach to Responses 5-1
Coping and Adaptation 5-1
"No Regrets" and "Multiple Benefit" Strategies 5-2
No Regrets Strategies 5-2
Multiple Benefits Logic 5-3
The Art of the Long View: Creating Scenarios for Alternative California Futures 5-3
Public Education 5-4
Experts and Professional Groups are Paying Attention 5-6
California Decision-Makers are Listening 5-6
Public Information: Response Strategies for Extreme Heat Conditions 5-7
California Pilot Project on the Use of Climate Forecast Information (NOAA) 5-8

Restoring Ecosystems and Building Resilience 5-9

An Evolving Focus on Multiple-Factor Risk Assessments and Regulatory Strategies 5-13

Building Resilience in the Urban Infrastructure 5-14
Land-Use Planning and Design 5-14
Urban Design and Stormwater Runoff 5-18
Reducing Urban Heat Island Impacts 5-21
Green Building 5-22
The California Blueprint for Green Buildings 5-26
Land-Use Planning in Specific Regions 5-28
Coastal Land-Use Planning 5-28
Planning in Fire-Prone Regions 5-29

Response Strategies for Water 5-30
Building Resilience in Water Systems 5-30
Addressing Multiple Stresses 5-31
Design Systems for Flexibility 5-31
Plan and Invest for Multiple Benefits 5-32
Water Policy, Planning, and Management 5-32
Economics and Water 5-35
Understanding Water Needs and Demand 5-35
The Role of Markets and Economics 5-36
Pricing, Demand Elasticity, and Supply "Shortages" 5-37
Water Transfers, Banking, and Marketing 5-38
Water Transfers 5-38
Water Banks 5-39
Water Markets 5-40
Water System Costs, Policy Planning, and Economic Models 5-41
Using Market Tools 5-42
Demand Management, Conservation, and Efficiency 5-43
Technology: New Capabilities in Efficiency 5-43
Stormwater Management Strategies 5-46
Public Education 5-50
Re-Operation of Water Systems 5-51

Policy Strategies for Multiple Benefits and No Regrets Responses 5-52
California Energy Commission 5-52
Greenhouse Gas Inventory 5-53
California Climate Registry 5-53
Policy Challenges: Overcoming Market and Institutional Barriers 5-53
Regional Scale Research and Responses 5-54
Statutory Authority for Emergency Response 5-55
Summary 5-56
Sources 5-57

VI. Research Priorities

Research Recommendations 6-1
Ecosystems 6-1
Water Systems 6-3

Modeling Regional Climate Change 6-6
The Economics of Climate Change Adaptation in California 6-7

Appendix

Appendix 1 Key Findings of the US National Assessment Synthesis Report A-1

Appendix 2 Stakeholder Involvement in the Regional Assessment A-4
Meetings and Presentations

Appendix 3 California Regional Workshop A-7
Steering Committee A-8
Advisory Committee A-10
Workshop Agenda A-12
Workshop Participants A-18

Executive Summary

Climate change and variability will have important implications for California. The state is one of the most diverse regions – ecologically, geographically, and culturally – of any in the world. California's 1.3 trillion dollar economy is the largest in the nation, and it would rank fifth in the G-7 group of the seven largest OECD economies if it were an independent country.[1] It has the largest population and the greatest diversity of people and environments of any state. A changing climate will potentially impact these people, places, and valuable systems.

Key findings of the California Assessment

The climate is changing. Climate change and variability pose significant potential challenges to California's businesses, communities, and natural resource and ecological systems.

We need to learn more about the dynamics of climate systems, and the models we use need to be improved to more accurately represent changes and interactions at a regional scale.

Building resilience in critical systems is a good strategy and a good investment. We currently have enough information to start responding to climate change through cost-effective "no regrets" and "multiple-benefits" strategies.

California's water systems are over-appropriated, and water management will remain a critically important issue in California. Climate change will provide new and uncertain challenges. Opportunities exist for efficiency improvements in all water-use sectors.

In California, there is a broad and growing recognition of the need to restore and protect the environment while achieving productivity and profitability in the economy. There are measures we should undertake now, both to hedge our bets, and because they are good investments.

New partnerships between business, government, communities, non-profit organizations, and the research community will be an important feature of successful research efforts and policy responses to climate change.

Background: The U.S. Climate Change Assessment Process

The United States Global Change Research Program (USGCRP) and the White House Office of Science and Technology (OSTP) organized a nation-wide program, in response to direction from Congress, to assess the possible impacts of climate change and variability on the United States

and its trust territories.[2] California was designated as a "region" for purposes of the national assessment. This regional assessment is part of the larger U.S. effort. A summary national assessment report, *Climate Change Impacts on the United States*, was issued by the National Assessment Synthesis Team in 2001.[3]

The National assessment, and the regional and sectoral assessments in the U.S., were asked to address four general questions:

Four Key Questions Addressed

1. Identify current stresses affecting the region, its natural resources, and economic sectors. (e.g.: issues such as water scarcity.)
2. Consider how climate variability and climate change might either amplify or mitigate these stresses, or create new ones.
3. Identify new information that would allow people and organizations to better understand the linkage between current stresses and climate change and variability.
4. Identify beneficial strategies that will help address the stresses created by climate change as well as by non-climate pressures.

The California assessment convened a representative cross-section of California's stakeholders – including business, government, non-governmental organizations, and science communities – to address the issue of potential climate change and variability as outlined in the four questions above. The findings are presented in detail in the California Assessment Report.

Scientific Basis for Concern

There is broad scientific agreement that global warming is occurring and that climate change and variability pose important challenges. The U.S. National Research Council's Committee on the Science of Climate Change confirmed in its 2001 report, *Climate Change Science: An Analysis of Some Key Questions*, that "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising."[4]

The projected rate of warming – 1.4 to 5.8 °C (2.5 to 10.4 °F) – is much greater than the observed changes during the 20th century and is "very likely to be without precedent during at least the last 10,000 years."[5]

The IPCC assessment indicates the following implications of global warming:

IPCC Projections

(IPCC Third Assessment, 2001)[6]

- Average global temperatures will increase between 1.4 to 5.8 °C (2.5 to 10.4 °F).
- More El Niño-like warming in the eastern tropical Pacific, and greater extremes of drying and heavy rainfall.
- Increased precipitation over northern mid to high latitudes and in Antarctica, with larger year-to-year variations worldwide.
- Weakening of ocean circulation patterns which bring warm tropical waters to high latitudes in the Northern Hemisphere.
- Northern Hemisphere snow cover, glaciers, ice caps and sea ice are projected to decrease. However, Antarctica is likely to gain mass.
- Global mean sea level is projected to rise by 0.09 to 0.88 meters (3.5 to 35 inches), primarily due to thermal expansion and glacial and ice sheet melting. (This figure is actually slightly lower than the 1992 scenarios predicted, due primarily to more precise modeling.)

Potential Impacts

There are a wide range of potential impacts to California's critically important natural resource systems, economic and social systems, and ecosystems that may be caused by climate change and variability.

- Water systems are critically important to the environment and to the economy and human welfare. Climate change and variability will likely impact the timing, amounts, and form of precipitation as well as its quality and uses.

- All ecosystems in California, whether natural or managed, will likely be affected by climate change and variability. Temperature changes and shifting precipitation patterns will alter plant and animal communities. Plants and animals, already pressured by human encroachment, will be further stressed by climate change and variability. Wildlife will have to adapt to changing habitats. Some species will move, others may alter their behavior. Some may not be able to adapt. The number of threatened and endangered species in the state, already the largest in the contiguous 48 states, could rise significantly due these combined stresses.[7]

- Extreme events, such as floods, droughts, and wildfires may become more frequent and intense.

- California relies on a complex set of infrastructure systems for transportation, communications, water delivery, electricity transmission, natural gas and oil delivery, and much more. These systems are interconnected, such that when one fails, others are impacted. Both extreme events and long-term changes in climate will impact these systems.

- From tourism to agriculture, the potential implications of climate change and variability are tied to impacts on natural systems. The linkage of these potential impact areas makes it difficult to neatly separate the topics for discussion in this assessment. Potential impacts to water systems, for example, will influence virtually every other sector.

- Human health in the California region is likely to be impacted by climate change and variability. Greater climate variability and changes in climate patterns will potentially cause both direct and indirect effects. Direct health impacts due to climate change include extreme events, such as storms resulting in flooding and landslides, heat waves and droughts resulting prolonged high temperatures and increased fire frequency and intensity. Secondary or indirect effects include damages to infrastructure causing, for example, sanitation and water treatment problems leading to an increase in water-borne infections. Air quality impacts such as increases in tropospheric, (i.e., ground-level) ozone due to higher temperatures may also cause secondary health impacts.

Developing Informed and Systematic Response Strategies

In considering appropriate strategies to deal with climate change, whether they are labeled "response" or "coping" or "adaptation", we must consider the nexus between sensitivity to changes, capacity to change or adapt, and vulnerability to change. These factors will inform cost/benefit estimates and the social and political assessment of acceptability of risk. Ultimate action on responses will also be driven by a sense of ethics and morals.

Economic activities, the physical infrastructure, and natural systems in California are inextricably linked. A good understanding of the dynamics of these systems is essential, as is a clear sense of their interrelationships. These concepts apply as much to business enterprises as they do to ecosystems. The goal of California decision-makers and stakeholders should therefore be to craft investment and policy strategies to maintain ecosystem health, productive capacity, and quality of life. These decisions should in turn be based on an accurate scientific understanding of the issues. To the extent that we are learning and living by "adaptive" management, we need to maximize the level of resilience in systems.

Research Recommendations

A priority for on-going research will be to better understand and define the dynamics of climate change and the *degree of sensitivity* of key systems (natural and human), the *potential for adaptability*, and *the vulnerability of these systems*.

Research is needed both to understand the changes that are occurring and to provide the basis for effective and efficient decision-making. Specific recommendations are provided for four topic areas: ecosystems, water, climate modeling, and economics.

An Ongoing Process

This assessment is one step in an ongoing process. To both understand the complex dynamics of the systems involved, and to respond effectively, dialogue and communication of information is critical.

The stakeholder approach employed in the national, regional, and sectoral assessments has been highly successful in facilitating an improved understanding of the science and of the implications of climate change and variability. Important questions and information were provided to scientists by practitioners in various fields. Scientists provided information based on research and analysis. The interaction and exchange of information was extremely valuable.

This assessment of the potential implications of climate change and variability in California should therefore be considered on step in an ongoing process.

Sources

[1] Based on: California figure; California Technology, Trade, and Commerce Agency. *California: An Economic Profile*. January 2002. OECD countries from Organization of Economic Cooperation and Development. OECD Statistics, GDP, January 2002. OECD at (http://www.oecd.org/std/gdp.htm), California at http://commerce.ca.gov/state/ttca

[2] *U.S. Global Change Research Program Act of 1990.* "Public Law 101-606 (11/16/90) 104 Stat. 3096-3104. An Act to require the establishment of a United States Global Change Research Program aimed at understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment, to promote discussions toward international protocols in global change research, and for other purposes."

[3] National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

[4] National Research Council, 2001. *Climate Change Science: An Analysis of Some Key Questions*, Committee on the Science of Climate Change, Division on Earth and Life Studies, National Academy Press, 2101 Constitution Avenue, N.W., Lockbox 285, Washington, D.C. 20055, (800) 624-6242, http://www.nap.edu

[5] Intergovernmental Panel on Climate Change. "Summary for Policy Makers. A Report of Working Group I." January 2001. http://www.met-office.gov.uk/sec5/CR_div/ipcc/wg1/

[6] Intergovernmental Panel on Climate Change. "Summary for Policy Makers. A Report of Working Group I." January 2001. http://www.met-office.gov.uk/sec5/CR_div/ipcc/wg1/

[7] The official California listing of Endangered and Threatened animals is contained in the California Code of Regulations, Title 14, Section 670.5. The official federal listing of Endangered and Threatened animals is published in the Federal Register, 50 CFR 17.11. See: the following web sites for full listings: Plants: http://www.dfg.ca.gov/whdab/html/plants.html Animals; http://www.dfg.ca.gov/whdab/html/animals.html

I. The United States Global Change Research Program and the Assessment of Potential Impacts of Climate Change and Variability

> *"Humanity's influence on the global climate will grow in the coming century. Increasingly, there will be significant climate-related changes that will affect each one of us. We must begin now to consider our responses, as the actions taken today will affect the quality of life for us and future generations."*
>
> U.S. National Assessment, *Climate Change Impacts on the United States* [1]

Introduction: The U.S. Climate Change Assessment Process

The United States Global Change Research Program (USGCRP) and the White House Office of Science and Technology (OSTP) organized a nation-wide program in response to direction from Congress to assess the possible impacts of climate change and variability on the United States and its trust territories. California was designated as a region for purposes of the national assessment. This regional assessment is part of the larger U.S. effort. The national assessment effort is outlined here to provide context for the California regional assessment.

The *Global Change Research Act of 1990* requires the federal government to investigate the potential impacts of global climate change and variability.[2] Federal agencies were directed to develop and coordinate "a comprehensive and integrated research program that will assist the nation and the world to understand, assess, predict, and respond to human-induced and natural process of global change." The law "gave voice to early scientific findings that human activities were starting to change the global climate:"[3]

> (1) Industrial, agricultural, and other human activities, coupled with an expanding world population, are contributing to processes of global change that may significantly alter the Earth habitat within a few generations;
>
> (2) Such human-induced changes, in conjunction with natural fluctuations, may lead to significant global warming and thus alter world climate patterns and increase global sea levels. Over the next century, these consequences could adversely affect world agricultural and marine production, coastal habitability, biological diversity, human health, and global economic and social well-being.[4]

The background and congressional mandate is as follows:

National Assessment of the Consequences of Climate Variability and Change for the United States[5]

The influence of climate permeates life and lifestyles in the U.S. Year-to-year variations are reflected in such things as the number and intensity of storms, the amount of water flowing in our rivers, the extent and duration of snow cover, and the intensity of waves that strike our coastal regions. Science now suggests that human activities are causing the climate to change. Although the details are still hazy about how much the changes will be in each region of the country, changes are starting to become evident. Temperatures have increased in many areas, snow cover is not lasting as long in the spring, and total precipitation is increasing, with more rainfall occurring in intense downpours. These changes appear to be affecting plants and wildlife. There is evidence of a longer growing season in northern areas and changing ranges for butterflies and other species. The international assessments of the Intergovernmental Panel on Climate Change (http://www.ipcc.ch) project that these changes will increase over the next 100 years.

To address these issues, Congress established the U.S. Global Change Research Program (USGCRP) and instructed the Federal research agencies to cooperate in developing and coordinating "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural process of global change." Further, the Congress mandated that the USGCRP "shall prepare and submit to the President and the Congress an assessment which:

1) integrates, evaluates, and interprets the findings of the Program and discusses the scientific uncertainties associated with such findings;
2) analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and
3) analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years." The USGCRP's National Assessment of the Potential Consequences of Climate Variability and Change, which is focused on answering the question about why we should care about and how we might effectively prepare for climate variability and change, is being conducted under the provisions of this Act."

The USGCRP includes the following federal agencies and departments:

Federal Agencies Participating in the USGCRP

National Science Foundation
National Aeronautics and Space Administration
National Oceanic and Atmospheric Administration
Environmental Protection Agency
Department of Energy
Department of State
Department of Defense
Department of the Interior
Department of Agriculture
Department of Transportation
Office of Management and Budget
Office of Science and Technology Policy
Council on Environmental Quality
National Institute of Environmental Health Sciences

Key Questions Addressed in the Assessment

The National assessment, and the regional and sectoral assessments in the U.S., were asked to address four general questions:

Four Key Questions Addressed

1. Identify current stresses affecting the region, its natural resources, and economic sectors. (e.g.: issues such as water scarcity.)
2. Consider how climate variability and climate change might either amplify or mitigate these stresses, or create new ones.
3. Identify new information that would allow people and organizations to better understand the linkage between current stresses and climate change and variability.
4. Identify beneficial strategies that will help address the stresses created by climate change as well as by non-climate pressures.

Goals of the Assessment Process

The goals of the assessment process are to:

1) Convene a representative cross-section of California's stakeholder, government, and science communities to address the issue of potential climate change as outlined in the four topics above;

2) Provide information and support a process of collaborative activities which will aid decision-makers, businesses, public interest organizations, and citizens in taking climate change and variability into account in planning for the future;

3) Provide a forum and process for the identification of research needs and priorities to better serve the concerns of California stakeholders; and

4) Foster and support an on-going effort to address climate change impacts in California. We plan to establish a dialogue between stakeholders, researchers, and government institutions to discuss how we might adapt to those changes to assure that California maintains its strong economy, preserves and restores its environmental health, and continues to be a place where people live and prosper.

The Assessment's purpose is to synthesize, evaluate, and report on what we presently know about the potential consequences of climate variability and change in the U.S. in the 21st century. It has sought to identify key climatic vulnerabilities of particular regions and sectors, in the context of other changes in the nation's environment, resources, and economy. It has also sought to identify potential measures to adapt to climate variability and change. Finally, because present knowledge is limited, the assessment has sought to identify the highest priority

uncertainties about which we must know more to understand climate impacts vulnerabilities, and our ability to adapt.[6]

Climate Observations

The U.S. assessment is based on both direct measurements and indicators.

> Climatologists use two types of data to monitor climate change. The first are historical measurements of temperature, precipitation, humidity, pressure, and wind speed taken at thousands of locations across the globe. Because observing methods, instruments, and station locations have changed over time, climatologists use various methods to crosscheck and corroborate these historical data sets. For example, satellite and balloon records confirm that the planet has been warming for the past four decades, although rates of atmospheric and surface warming differ somewhat from decade to decade. To peer further back into the past, climatologists also analyze physical, biological, and chemical indicators. For example, past climate conditions can be inferred from the width of tree rings, air trapped in ancient ice cores, and sediment deposited at the bottom of lakes and oceans. Taken together, this information demonstrates that the Earth's climate over the past 10,000 years has been relatively stable compared to the 10,000 years that preceded this period and compared to the 20th century.[7]

The assessment also utilizes computer models which simulate climate variable. Two global circulation models (GCMs) were chosen for the U.S. assessment. Additional modeling was conducted using other GCMs as well as described below:

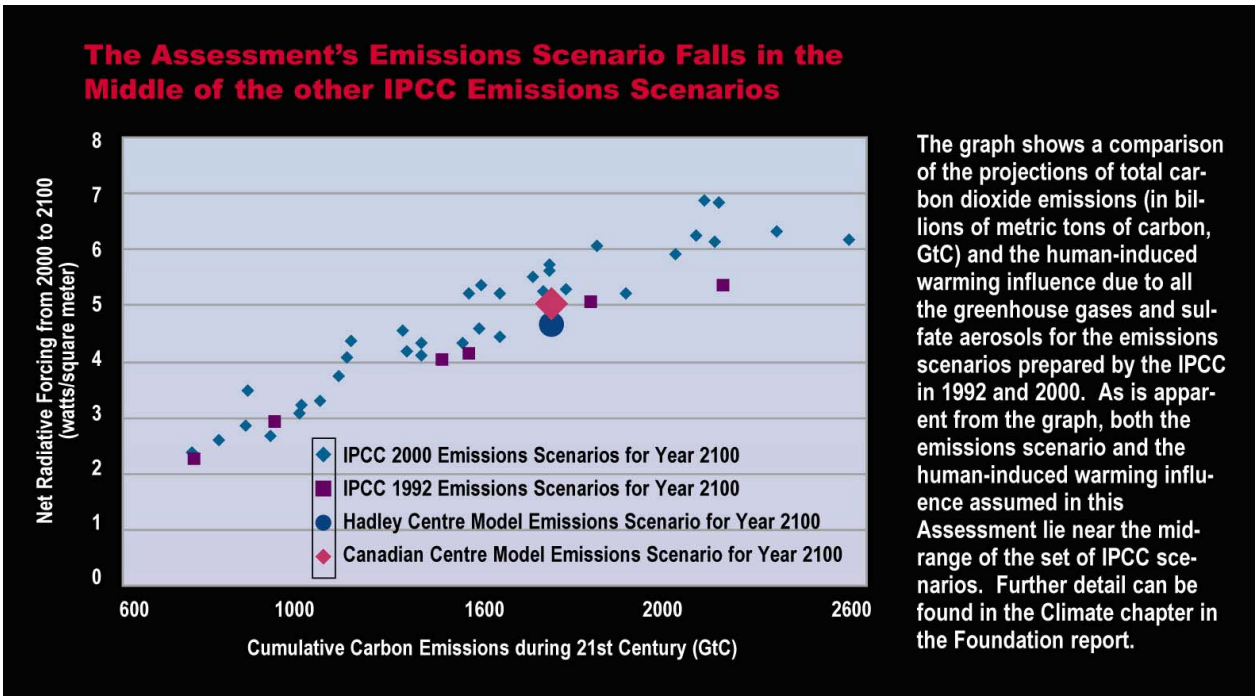
Climate Models Used in the U.S. Assessment[8]

Climate models continue to improve, and assumptions about future greenhouse gas emissions continue to evolve. The two primary models used to project changes in climate in this Assessment were developed at the Canadian Climate Center and the Hadley Center in the United Kingdom. They have been peer-reviewed by other scientists and both incorporate similar assumptions about future emissions. These models were the best fit to a list of criteria developed for this Assessment. Climate models developed at the National Center for Atmospheric Research (NCAR), NOAA's Geophysical Fluid Dynamics Laboratory (GFDL), NASA's Goddard Institute for Space Studies (GISS), and Max Planck Institute (MPI) in Germany, were also used in various aspects of the Assessment.

While the physical principles driving these models are similar, the models differ in how they represent the effects of some important processes. Therefore, the two primary models paint different views of 21st century climate. On average over the US, the Hadley model projects a much wetter climate than does the Canadian model, while the Canadian model projects a greater increase in temperature than does the Hadley model. Both projections are plausible, given current understanding. In most climate models, increases in temperature for the US are significantly higher than the global average temperature increase. This is due to the fact that all models project the warming to be greatest at middle to high latitudes, partly because melting snow and ice make the surface less reflective of sunlight, allowing it to absorb more heat. Warming will also be greater over land than over the oceans because it takes longer for the oceans to warm.

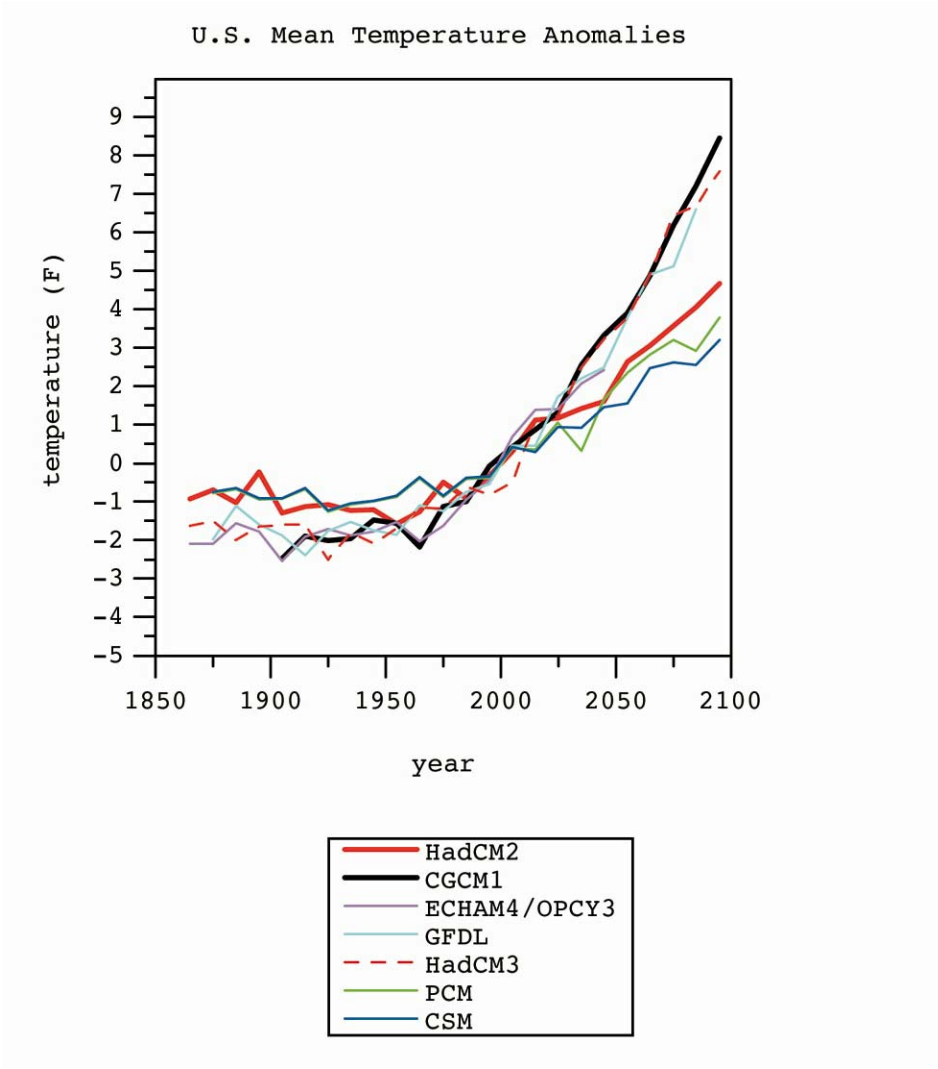
The Canadian and Hadley model runs used in the national assessment "business as usual" scenarios assumed a one-percent-per-year increase in carbon dioxide equivalence and a doubling of sulfur emissions by 2100. These assumptions match the Intergovernmental Panel on Climate Change.[9] The assessment also utilized the National Center for Atmospheric Research (NCAR) CSM "stabilization run".

A review of strengths and limitations of GCMs, particularly the Canadian and the Hadley models, may be found at the national assessment web site http://www.nacc.usgcrp.gov/scenarios/ and http://www.gcrio.org/nationalassessment/. See also a review by Doherty and Mearns.[10] The following graph shows a comparison of projections from IPCC (1992 and 2000) and the Hadley and Canadian models.[11]



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

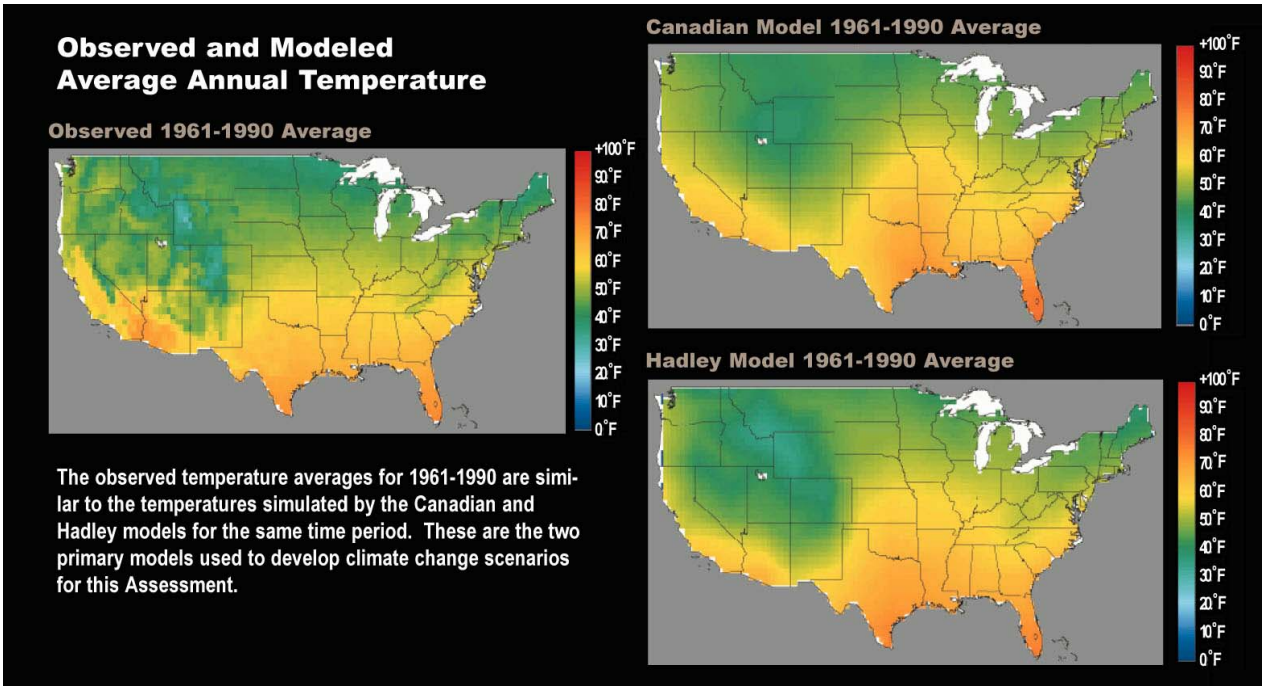
Temperature is plotted on the graph below based on a larger number of computer model runs. As is evident, the trends are roughly consistent across the models.[12]



Simulations from leading climate models of changes in decadal average surface temperature for the conterminous US (excluding Alaska and Hawaii) based on historic and projected changes in atmospheric concentrations of greenhouse gases and sulfate aerosols. The heavy red and black lines indicate the primary models used by the National Assessment. For the 20th century, the models simulate a US temperature rise of about 0.7 to 1.9°F, whereas estimates from observations range from 0.5 to 1.4°F; estimates for the global rise are 0.9 to 1.4°F for models and 0.7 to 1.4°F for observations, suggesting reasonable agreement. For the 21st century, the models project warming ranging from 3 to 6°F for the globe and 3 to 9°F for the US. The two models at the low end of this range assume lower emissions of greenhouse gases than do the other models.

Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

The following images indicate a reasonable correlation of historic and modeled temperatures.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Both the Canadian and Hadley model scenarios project substantial warming during the 21st century. The warming is considerably greater in the Canadian model, with most of the continental US experiencing increases from 5 to 15°F. In this model, the least warming occurs in the West and along the Atlantic and Gulf Coasts. In the Hadley model, annual temperatures are projected to increase from 3 to 7°F, with the largest warming occurring in the western half of the country.

The U.S. National assessment reached the following conclusions regarding potential impacts: [13]

> Long-term observations confirm that our climate is now changing at a rapid rate. Over the 20th century, the average annual US temperature has risen by almost 1°F (0.6°C) and precipitation has increased nationally by 5 to 10%, mostly due to increases in heavy downpours. These trends are most apparent over the past few decades. The science indicates that the warming in the 21st century will be significantly larger than in the 20th century. Scenarios examined in this Assessment, which assume no major interventions to reduce continued growth of world green-house gas emissions, indicate that temperatures in the US will rise by about 5-9°F (3-5°C) on average in the next 100 years, which is more than the projected *global* increase. This rise is very likely to be associated with more extreme precipitation and faster evaporation of water, leading to greater frequency of both very wet and very dry conditions.

> Major alterations to natural ecosystems due to climate change could possibly have negative consequences for our economy, which depends in part on the sustained bounty of our nation's lands, waters, and native plant and animal communities.

Summary

The United States Global Change Research Program (USGCRP), in response to direction from Congress, is assessing the possible impacts of climate change and variability on the United States and its trust territories. California was designated as a region for purposes of the assessment.

The California regional assessment examines the potential implications of changes in climate and of changes in climate variability. It includes an analysis of the stresses, implications, and coping and adaptation strategies as set forth in the questions posed for the assessment.

The next section sets for the science of climate change, which is used as a starting point for this assessment.

Sources

[1] National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

[2] *U.S. Global Change Research Program Act of 1990.* "Public Law 101-606 (11/16/90) 104 Stat. 3096-3104. An Act to require the establishment of a United States Global Change Research Program aimed at understanding and responding to global change, including the cumulative effects of human activities and natural processes on the environment, to promote discussions toward international protocols in global change research, and for other purposes."

[3] Michael MacCracken, National Assessment Coordination Office.

[4] *U.S. Global Change Research Program Act of 1990.* "Public Law 101-606 (11/16/90) 104 Stat. 3096-3104.

[5] Michael MacCracken, National Assessment Coordination Office. United States Global Change Research Program (USGCRP).

[6] National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program (USGCRP). Cambridge University Press. p.2.
http://www.usgcrp.gov/usgcrp/Library/nationalassessment/

[7] National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program (USGCRP). Cambridge University Press.

[8] National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program (USGCRP). Cambridge University Press. p.16.

[9] Intergovernmental Panel on Climate Change (IPCC). 1996. Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the *Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, New York.

[10] Doherty, R. and L.O. Mearns. 1999. A comparison of simulations of current climate from two coupled atmosphere-ocean global climate models against observations and evaluation of their future climates. Report to the National Institute for Global Environmental Change (NIGEC). National Center for Atmospheric Research, Boulder, Colorado.
(February).

[11] National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program (USGCRP). Cambridge University Press.

[12] National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program (USGCRP). Cambridge University Press.

[13] National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program (USGCRP). Cambridge University Press. p.6.

II. Climate Change Science

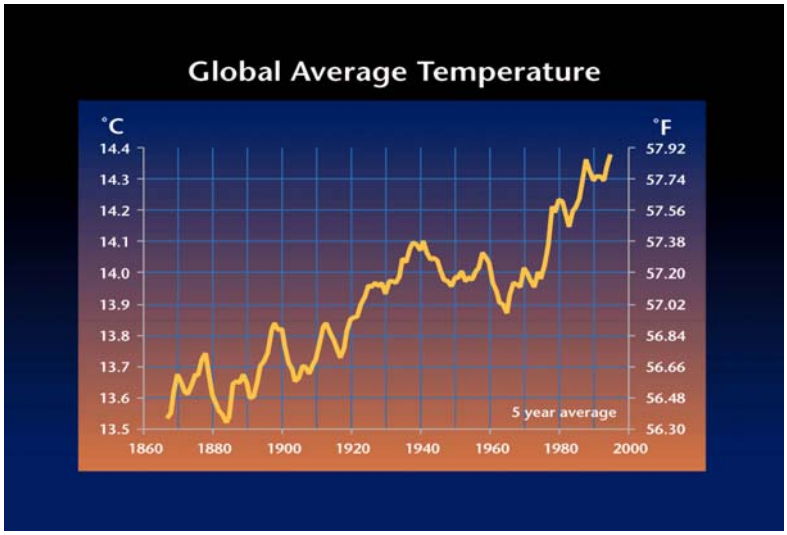
Introduction

This section of the California assessment examines the science of climate change and variability. The findings of the U.S. and international scientific community are presented as a basis for further discussion in following sections of the potential implications for the California region.

There is broad scientific agreement that global warming is occurring and that climate change and variability pose important challenges. The U.S. National Research Council's (NRC) Committee on the Science of Climate Change confirmed in its report *Climate Change Science: An Analysis of Some Key Questions* that "Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. Temperatures are, in fact, rising."[1] The NRC committee's report confirmed the work of the Intergovernmental Panel on Climate Change (IPCC), the international science effort examining the science of climate change. The committee found that the IPCC report "is an admirable summary of research activities in climate science."[2] The U.S. National Assessment Synthesis Team provides the following summary in: *Climate Change Impacts on the United States.*

The Climate Is Changing[3]

As we add more CO_2 and other heat-trapping gases to the atmosphere, the world is becoming warmer (which changes other aspects of climate as well). Historical records of temperature and precipitation have been extensively analyzed in many scientific studies. These studies demonstrate that the global average surface temperature has increased by over 1ºF (0.6ºC) during the 20th century. About half this rise has occurred since the late 1970s. Seventeen of the eighteen warmest years in the 20th century occurred since 1980. In 1998,the global temperature set a new record by a wide margin, exceeding that of the previous record year, 1997, by about 0.3ºF (0.2ºC).



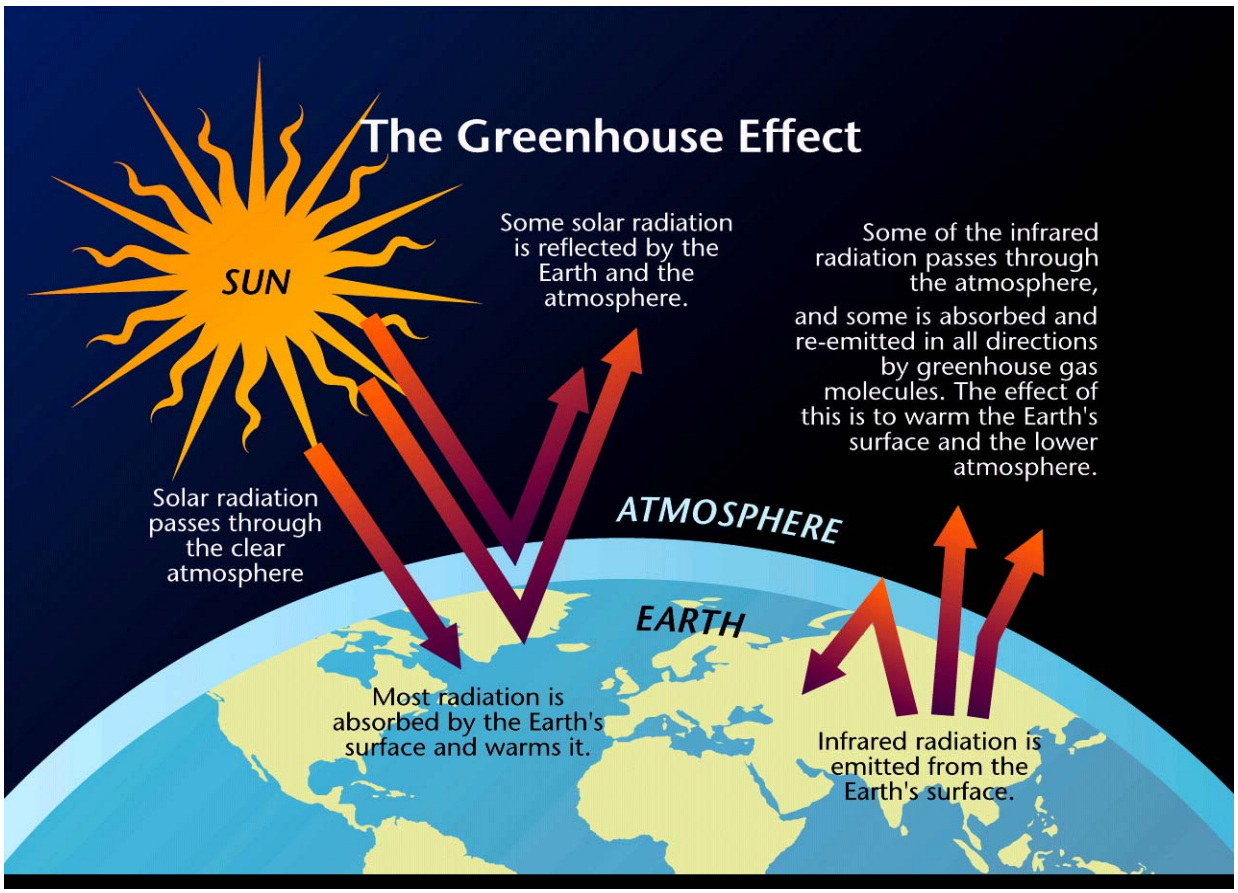
Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

The Greenhouse Effect

Global warming, and climate changes resulting from it, is influenced by different factors. The focus of this assessment is on the *implications* of climate change and variability, whatever its causes. The basic concept, as illustrated in the schematic below, is that the earth's temperature is regulated in part by gasses that trap heat in the earth's atmosphere. This *greenhouse effect* allows the earth's temperature to be in the range to which all life on earth has evolved. Increased concentrations of specific gasses increase the heat-trapping ability of the atmosphere and are responsible for increasing temperatures.

Climate Change and the Greenhouse Effect[4]

Earth's climate is determined by complex interactions between the sun, oceans, atmosphere, land, and living things. The composition of the atmosphere is particularly important because certain gases (including water vapor, carbon dioxide, methane, halocarbons, ozone, and nitrous oxide) absorb heat radiated from the Earth's surface. As the atmosphere warms, it in turn radiates heat back to the surface, to create what is commonly called the "greenhouse effect." Changes in the composition of the atmosphere alter the intensity of the greenhouse effect. Such changes, which have occurred many times in the planet's history, have helped determine past climates and will affect the future climate as well.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Scientific Analysis of Climate Change

Climate change and global warming have been studied by leading scientists for many years. The U.S. National Academy of Sciences published a *Program for Action* in 1975 acknowledging that humans could influence global climate.[5] It recommended a research program to improve our understanding of global systems.

The U.S. Senate held a symposium on climate change in 1979,[6] and the National Academy published *Changing Climate* by Revelle and Waggoner in 1983.[7] Five years later the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO).[8]

The Intergovernmental Panel on Climate Change[9]

The Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environmental Program (UNEP) and the World Meteorological Organization (WMO) in 1988 to assess the scientific, technical and socio-economic information relevant for the understanding of human induced climate change, its potential impacts and options for mitigation and adaptation. The IPCC has completed two full assessment reports, guidelines and methodologies, special reports and technical papers.[10] The IPCC has three working groups:

- Working Group I: The Science of Climate Change
- Working Group II: Impacts, Adaptation and Vulnerability
- Working Group III: Mitigation of Climate Change, and a
- Task Force on Greenhouse Gas Inventories

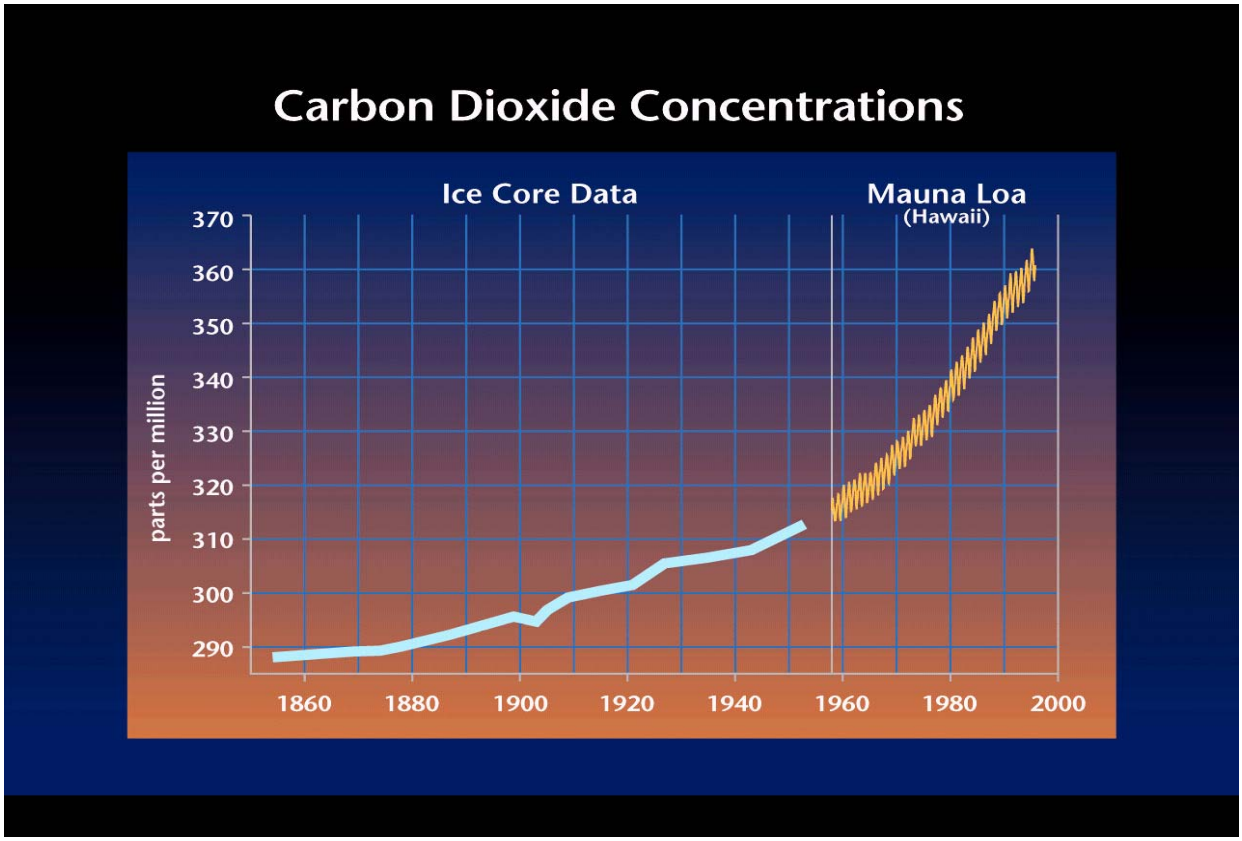
In 1992, the IPCC established several scenarios for global climate in the next 100 years which take into account low, medium, and high levels of human population growth, greenhouse gas emissions, and environmental sensitivities to atmospheric carbon dioxide concentrations. These scenarios projected that in the next century, average global surface temperatures would increase by 1° to 3.5° C (1.8° to 6.5° F). Since then, the state of knowledge about climate change and the sophistication of climate models have increased.

New scenarios developed for the third assessment by the IPCC (2001) indicate that for the period of 1990 to 2100 surface temperatures (averaged globally) will increase by 1.4 to 5.8 °C (2.5 to 10.4 °F) relative to 1990. Global mean sea level is projected to rise by 0.09 to 0.88 meters (3.5 to 35 inches), primarily due to thermal expansion and glacial and ice sheet melting. [11]

Global Warming Potential (GWP) of Greenhouse Gases

Greenhouse Gas	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	23
Nitrous oxide (N_2O)	296
HFC-23	12,000
HFC-125	3,400
HFC-134a	1,300
HFC-143a	4,300
HFC-152a	120
HFC-227ea	3,500
HFC-236fa	9,400
Perfluoromethane (CF_4)	5,700
Perfluoroethane (C_2F_6)	11,900
Sulfur Hexafluoride (SF_6)	22,200

Source: DOE 2001.[12]



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Carbon dioxide (CO_2) is one of several gasses that trap heat in the atmosphere. The other important heat trapping gasses and their forcing or warming potential are presented in the

following table from the National Research Council. The table indicates the approximate average time for removal of the gasses and the warming potential in Watts per square meter.

Removal Times and Climate Forcing Values for Specified Atmospheric Gases and Aerosols

Forcing Agent	*Approximate Removal Times **	*Climate Forcing (W/m 2) Up to the year 2000*
Greenhouse Gases		
Carbon Dioxide	>100 years	1.3 to 1.5
Methane	10 years	0.5 to 0.7
Tropospheric Ozone	10-100 days	0.25 to 0.75
Nitrous Oxide	100 years	0.1 to 0.2
Perfluorocarbon Compounds (Including SF 6)	>1000 years	0.01
Fine Aerosols		
Sulfate	10 days	–0.3 to –1.0
Black Carbon	10 days	0.1 to 0.8

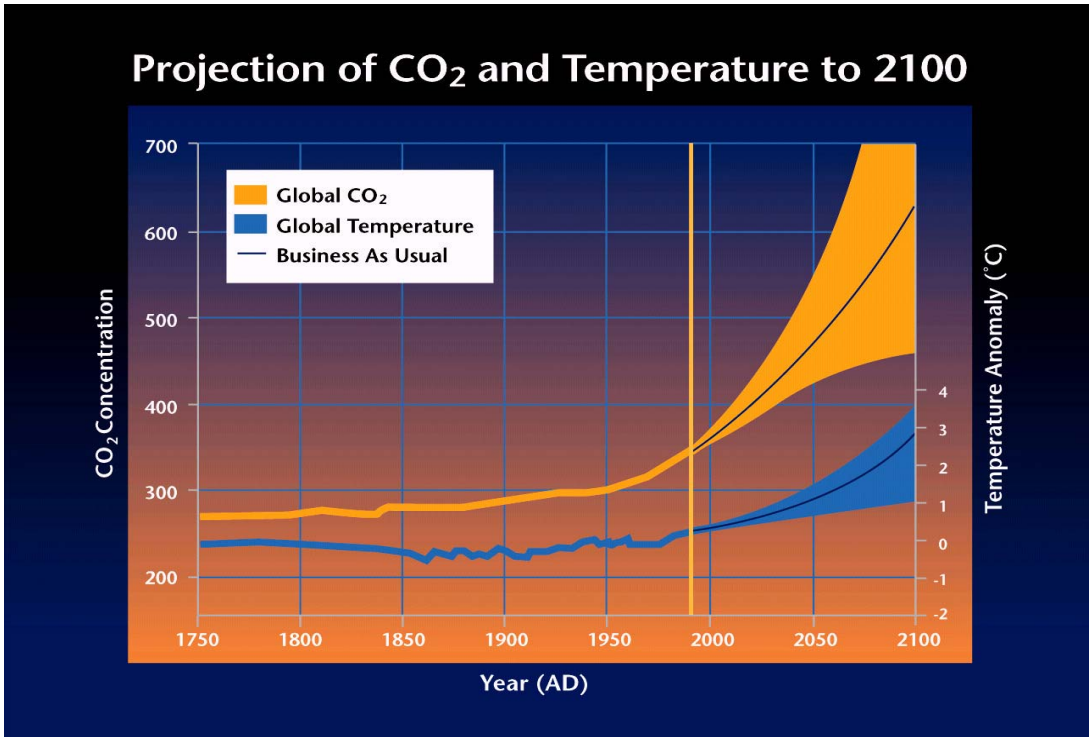
* A removal time of 100 years means that much, but not all, of the substance would be gone in 100 years. Typically, the amount remaining at the end of 100 years is 37%;after 200 years 14%;after 300 years 5%;after 400 years 2%.

Source: National Research Council, 2001. Climate Change Science: An Analysis of Some Key Questions, *Committee on the Science of Climate Change, Division on Earth and Life Studies,* National Academy Press, Table 1, p.3.

Human activities are linked to the changes that are taking place.

Human Activities Alter the Balance[13]

Humans are exerting a major and growing influence on some of the key factors that govern climate by changing the composition of the atmosphere and by modifying the land surface. The human impact on these factors is clear. The concentration of carbon dioxide (CO_2) has risen about 30% since the late 1800s. The concentration of CO_2 is now higher than it has been in at least the last 400,000 years. This increase has resulted from the burning of coal, oil, and natural gas, and the destruction of forests around the world to provide space for agriculture and other human activities. Rising concentrations of CO_2 and other greenhouse gases are intensifying Earth's natural greenhouse effect. Global projections of population growth and assumptions about energy use indicate that the CO_2 concentration will continue to rise, likely reaching between two and three times its late-19th-century level by 2100. This dramatic doubling or tripling will occur in the space of about 200 years, a brief moment in geological history.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Concerned about the scientific findings, the Council of the American Geophysical Union issued a "position statement" on climate change and greenhouse gases. The AGU warned as follows:[14]

> Present understanding of the Earth climate system provides a compelling basis for legitimate public concern over future global- and regional-scale climate changes resulting from increased concentrations of greenhouse gases. Some of these changes may be beneficial and others damaging for different parts of the world. However, the rapidity and uneven geographic distribution of these changes could be very disruptive.

Climate Scenarios

Scenarios, derived from the word "scene", are descriptions of possible futures. The usefulness of scenarios is primarily to provide a useful way to think about what may happen in the future under certain conditions. The scenarios employed in climate change analysis are based on specific assumptions, such as the rate of emissions influencing or *forcing* warming trends. (The various greenhouse gasses are converted to an *equivalent* of the warming impact of CO_2 for comparison purposes.) The models often refer to a *multiple* of the level of greenhouse gasses (in *equivalent* CO_2) relative to a base year, such as 1990. For example, a *two-times carbon dioxide* model run illustrates a scenario with twice the CO_2 equivalent warming.

What are scenarios and why are they used?[15]

Scenarios are plausible alternative futures – each an example of what might happen under particular assumptions. Scenarios are not specific predictions or forecasts. Rather, scenarios provide a starting point for examining questions about an uncertain future and can help us visualize alternative futures in concrete and human terms. The military and industry frequently use these powerful tools for future planning in high-stakes situations. Using scenarios helps to identify vulnerabilities and plan for contingencies.

Carbon Emissions and Concentrations[16]

Records of Northern Hemisphere surface temperatures, CO_2 concentrations, and carbon emissions show a close correlation. Temperature Change: reconstruction of annual-average Northern Hemisphere surface air temperatures derived from historical records, tree rings, and corals (blue), and air temperatures directly measured (purple). CO_2 Concentrations: record of global CO_2 concentration for the last 1000 years, derived from measurements of CO_2 concentration in air bubbles in the layered ice cores drilled in Antarctica (blue line) and from atmospheric measurements since 1957. Carbon Emissions: reconstruction of past emissions of CO_2 as a result of land clearing and fossil fuel combustion since about 1750 (in billions of metric tons of carbon per year).[17]

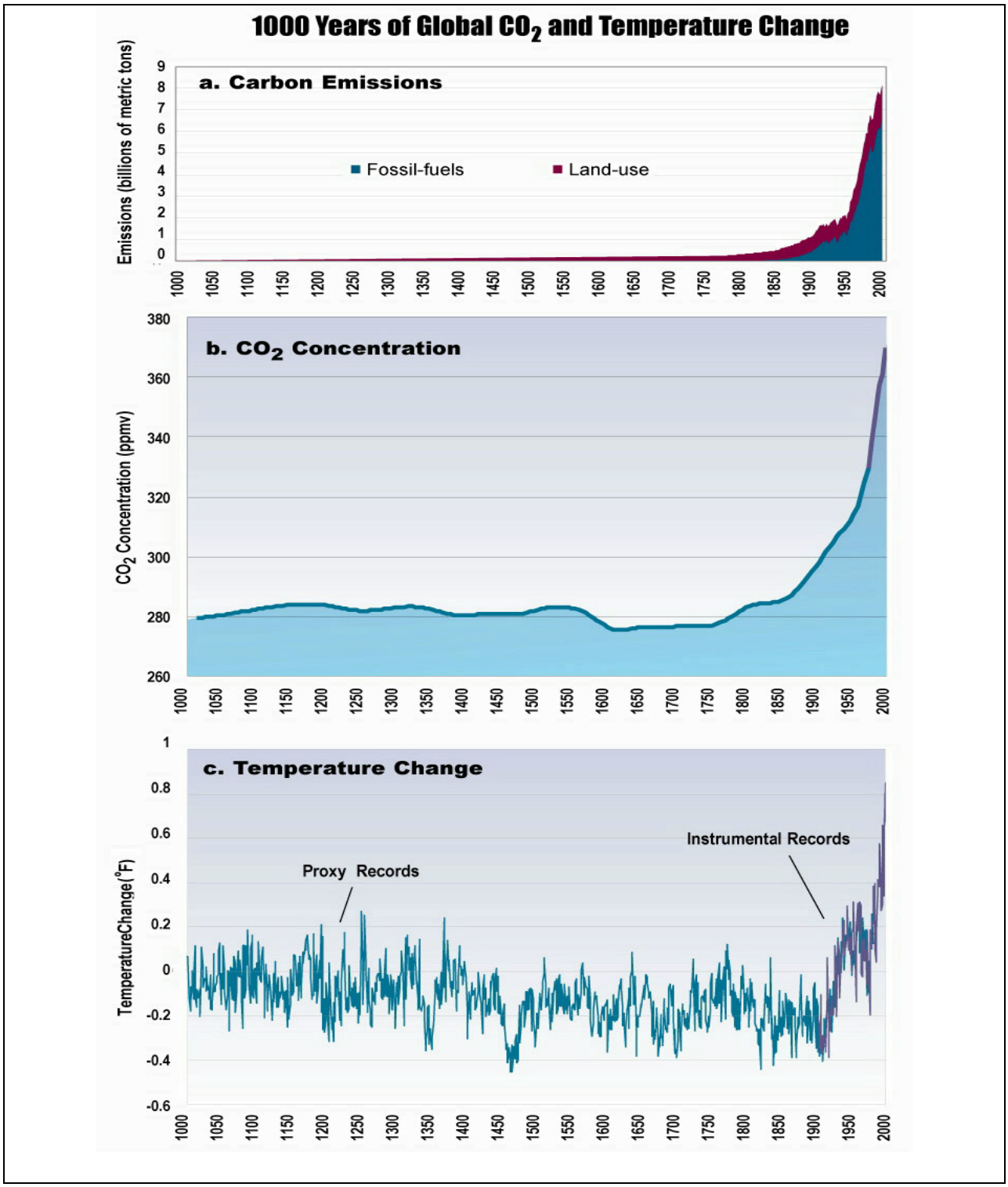
Global Warming and Rates of Change

The projected rate of warming – 1.4 to 5.8 °C (2.5 to 10.4 °F) – is much greater than the observed changes during the 20th century and is "very likely to be without precedent during at least the last 10,000 years, based on paleoclimate data."[18] (The IPCC uses the phrase "very likely" to indicate a scientific confidence level of 90 to 99 percent. See boxes on measuring and reporting uncertainty below.)

Climate is the average state of the atmosphere and the underlying land or water, on time scales of seasons and longer.[19]

"Climate" versus "Weather"

The terms climate and weather are often confused. Weather is the day-to-day phenomena we experience—sun, rain, fog, warm, cold, wind—that vary greatly. Climate is long-term statistical patterns of weather. Climate in California is influenced by global factors such as Earth's rotation and tilt and the state's latitude and proximity to the Pacific, as well as local topography and many other factors. While climate can also vary from year to year, there are weather trends we can expect in California—warmth in summer, Santa Ana winds in autumn, rain in winter. Climate is reflected in average temperatures, rainfall, and other weather events at a given location, and climate change is signaled by long-term changes in those averages.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

The IPCC scenarios yield global averages.[20] Regional variations could be dramatic. The warming in the northern regions of North America and northern and central Asia are projected to exceed global averages by more than 40 percent, whereas south and southeast Asia and South America will experience warming below the global average.

IPCC Projections

(IPCC Third Assessment, 2001)[21]

- Average global temperatures will increase between 1.4 to 5.8 °C (2.5 to 10.4 °F).
- More El Niño-like warming in the eastern tropical Pacific, and greater extremes of drying and heavy rainfall.
- Increased precipitation over northern mid to high latitudes and in Antarctica, with larger year-to-year variations worldwide.
- Weakening of ocean circulation patterns which bring warm tropical waters to high latitudes in the Northern Hemisphere.
- Northern Hemisphere snow cover, glaciers, ice caps and sea ice are projected to decrease. However, Antarctica is likely to gain mass.
- Global mean sea level is projected to rise by 0.09 to 0.88 meters (3.5 to 35 inches), primarily due to thermal expansion and glacial and ice sheet melting. (This figure is actually slightly lower than the 1992 scenarios predicted, due primarily to more precise modeling.)

Abrupt Changes and "Inevitable Surprises"

It is important to note that change will not necessarily occur in a steady and predictable fashion. A recent report from the National Research Council entitled *Abrupt Climate Change: Inevitable Surprises* concludes that:[22]

> Recent scientific evidence shows that major and widespread climate changes have occurred with startling speed. For example, roughly half the north Atlantic warming since the last ice age was achieved in only a decade, and it was accompanied by significant climatic changes across most of the globe. Similar events, including local warmings as large as 16ºC, occurred repeatedly during the slide into and climb out of the last ice age. Human civilizations arose after those extreme, global ice-age climate jumps.
>
> Abrupt climate changes were especially common when the climate system was being forced to change most rapidly. Thus *greenhouse warming and other human alterations of the earth system may increase the possibility of large, abrupt, and unwelcome regional or global climatic events.* The abrupt changes of the past are not fully explained yet, and *climate models typically underestimate the size, speed, and extent of those changes*. Hence, future abrupt changes cannot be predicted with confidence, and climate surprises are to be expected.

Thus, in addition to the kinds of gradual (albeit accelerated) centennial-scale climate changes projected by current climate models, Californians need to be aware of the possibility of much more sudden climate shifts. These shifts have a scientifically well-founded place among the possible futures facing the state and should be among the possibilities accommodated in planning and adaptation measures. They are most pronounced in records from the past ice ages, but less vigorous abrupt (rapid) climate changes have also characterized the climate of the present interglacial period.[23]

An example of the kind of change discussed in the NRC report is as follows:

National Research Council
Introduction to Abrupt Changes in the Earth's Climate

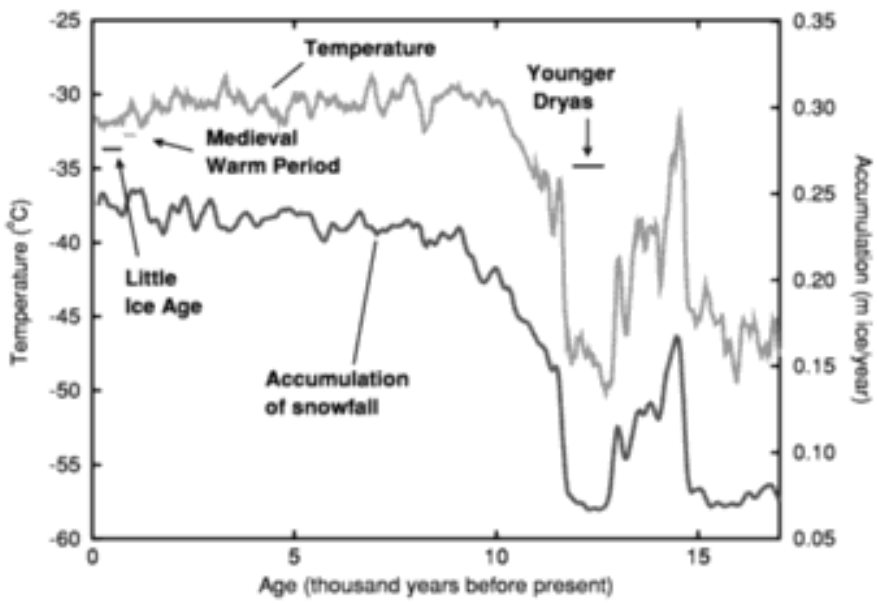


FIGURE 1.2 Climate changes in central Greenland over the last 17,000 years. Reconstructions of temperature and snow accumulation rate (Cuffey and Clow, 1997; Alley, 2000) show a large and rapid shift out of the ice age about 15,000 years ago, an irregular cooling into the Younger Dryas event, and the abrupt shift toward modern values. The 100-year averages shown somewhat obscure the rapidity of the shifts. Most of the warming from the Younger Dryas required about 10 years, with 3 years for the accumulation-rate increase (Figure 2.2). A short-lived cooling of about 6°C occurred about 8,200 years ago (labeled 8ka event), and is shown with higher time resolution in Figure 2.3. Climate changes synchronous with those in Greenland affected much of the world, as shown in Figures 2.1 and 2.3.

Source: National Research Council, Committee on Abrupt Climate Change, 2002. *Abrupt Climate Change: Inevitable Surprises*: National Academy Press, Washington, DC, p.15.

The IPCC Assessment

In May, 2001 the Bush Administration asked the National Research Council to review the IPCC work.[24] The Council assembled a distinguished panel of experts chaired by Dr. Ralph J. Cicerone, Chancellor of the University of California at Irvine and Daniel G. Aldrich Professor, Department of Earth System Science and the Department of Chemistry, to review the study.[25] The National Research Council's report, *Climate Change Science: An Analysis of Some Key Questions,* was issued by the Committee on the Science of Climate Change, Division on Earth and Life Studies in 2001. It is available from the National Academy at http://www.nap.edu.[26]

The committee addressed a series of specific questions regarding climate change science and the IPCC work. The key questions and findings follow:[27]

The National Research Council
Climate Change Science: An Analysis of Some Key Questions

Is climate change occurring? If so, how?
Weather station records and ship-based observations indicate that global mean surface air temperature warmed between about 0.4 and 0.8 °C (0.7 and 1.5 °F) during the 20th century. The ocean, which represents the largest reservoir of heat in the climate system, has warmed by about 0.05 °C (0.09 °F) averaged over the layer extending from the surface down to 10,000 feet, since the 1950s.

Are greenhouse gases causing climate change?
The IPCC 's conclusion that most of the observed warming of the last 50 years is likely to have been due to the increase in greenhouse gas concentrations accurately reflects the current thinking of the scientific community on this issue.

Despite the uncertainties, there is general agreement that the observed warming is real and particularly strong within the past 20 years. Climate change simulations for the period of 1990 to 2100 based on the IPCC emissions scenarios yield a globally-averaged surface temperature increase by the end of the century of 1.4 to 5.8 °C (2.5 to 10.4 °F) relative to 1990.

The predicted warming is larger over higher latitudes than over low latitudes, especially during winter and spring, and larger over land than over sea. Rainfall rates and the frequency of heavy precipitation events are predicted to increase, particularly over the higher latitudes. Higher evaporation rates would accelerate the drying of soils following rain events, resulting in lower relative humidities and higher daytime temperatures, especially during the warm season. The likelihood that this effect could prove important is greatest in semi-arid regions, such as the U.S. Great Plains. These predictions in the IPCC report are consistent with current understanding of the processes that control local climate.

What will be the consequences (e.g., extreme weather, health effects) of increases of various magnitude?
Global warming could well have serious adverse societal and ecological impacts by the end of this century, especially if globally-averaged temperature increases approach the upper end of the IPCC projections. Even in the more conservative scenarios, the models project temperatures and sea levels that continue to increase well beyond the end of this century, suggesting that assessments that examine only the next 100 years may well underestimate the magnitude of the eventual impacts.

What are the substantive differences between the IPCC Reports and the Summaries?
The committee finds that the full IPCC Working Group I (WGI) report is an admirable summary of research activities in climate science, and the full report is adequately summarized in the *Technical Summar*y.

The NRC committee made the following statements:[28]

> Greenhouse gases are accumulating in Earth's atmosphere as a result of human activities, causing surface air temperatures and subsurface ocean temperatures to rise. *Temperatures are, in fact, rising.*
>
> Human-induced warming and associated sea-level rises are expected to continue through the 21st century. Secondary effects are suggested by computer model simulations and basic physical reasoning. These include increases in rainfall rates and increased susceptibility of semi-arid regions to drought. The impacts of these changes will be critically dependent on the magnitude of the warming and the rate with which it occurs.
>
> The committee generally agrees with the assessment of human-caused climate change presented in the IPCC Working Group I (WGI) scientific report…

Measuring and Reporting Uncertainties

Uncertainty is measured and represented in research findings in different ways. The IPCC, USGCRP, Moss and Schneider, and others have developed specific scales and information to clarify the meanings of different terms. Several scales are presented below to assist in an effort to clarify the terminology.[29]

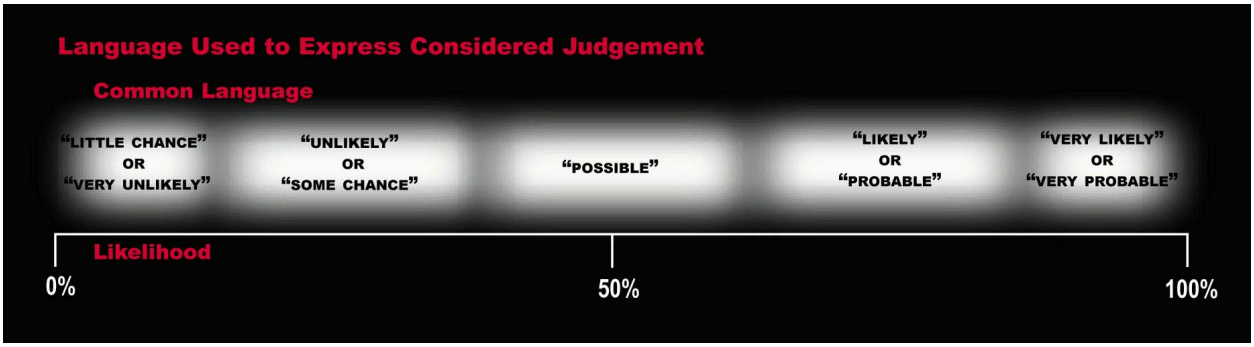
Quantitative Scales for Assessing Uncertainties

IPCC, Confidence Terms Probability or Confidence Limit[30]

Very High Confidence	1.00 to 0.95
High Confidence	0.95 to 0.67
Medium Confidence	0.67 to 0.33
Low Confidence	0.33 to 0.05
Very Low Confidence	0.05 to 0.00

USGCRP, Terms for Probability or Confidence Limit[31]

Very likely or very probable	>90%
Likely or probable	67 to 90%
Possible	34 to 66%
Unlikely or some chance	10 to 33%
Little chance or very unlikely	< 10%



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

IPCC: Qualitative Scales for Assessing Uncertainties[32]

High Confidence	Wide agreement, multiple findings, high degree of consensus, considerable evidence
Medium Confidence	Consensus, fair amount of information, other hypotheses cannot be ruled out conclusively
Low Confidence	Lack of consensus, serious competing ideas, limited evidence in support

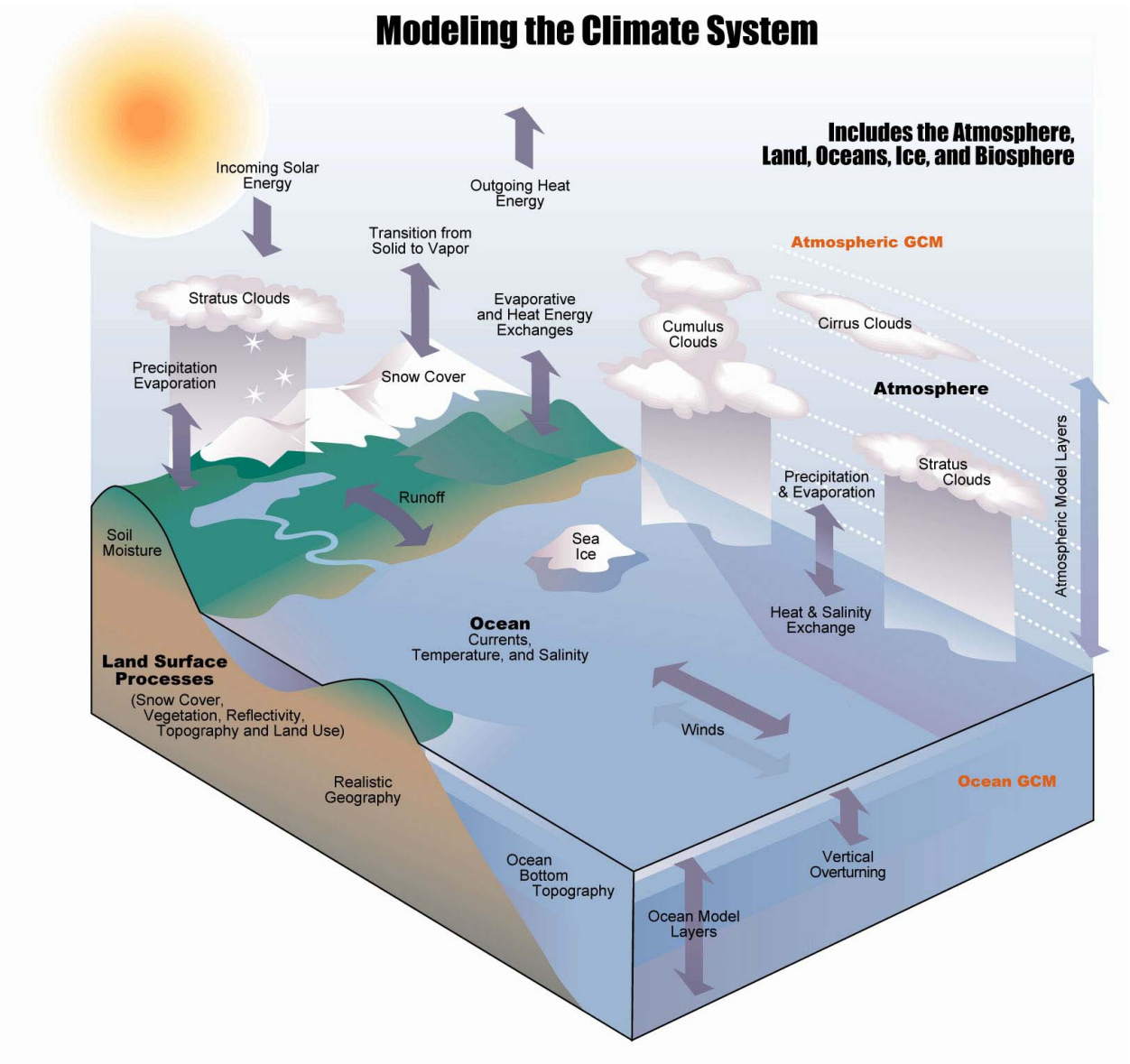
Moss and Schneider: Qualitative Terms[33]

Well established	Multiple lines of evidence, models consistent with observations
Established but incomplete	Models incorporate most known processes, one or more lines of evidence, observations somewhat consistent but incomplete
Competing explanations	Different models produce different results or incorporate different key processes
Speculative	Conceptually plausible ideas that have received little attention, or that are laced with difficult-to-reduce uncertainties

Modeling Climate Change

Scientists use models to better understand the dynamics of climate systems. The models are mathematical simulations of factors that effect, and are affected by, climate. They are scaled to different geographic areas, and they are *driven* by differing assumptions. Models are useful in improving our understanding of system dynamics, and they help us identify possible outcomes based on different assumptions.

The following schematic is a representation of the elements included in climate models. An important feature of the models is the ocean-atmosphere interactions as indicated.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Climate Models

Climate projections are made using general circulation models (GCMs) which use computerized mathematical models to simulate changes in temperature, precipitation, wind, ocean circulation, and other variables. The models incorporate known parameters and processes that govern climate as well as historical data. By introducing variables such as a buildup of greenhouse gases or a volcanic eruption, the models can provide a picture of future climate. GCMs, however, are simplified, incomplete projections that are not precise predictions. Many future variables are unknown, particularly greenhouse gas emissions. In recent years, GCMs have become increasingly sophisticated, and the scientific community's confidence in the projections has increased accordingly.

Regional or down-scaled models move the analysis from the global scale to a specific region. Topography (e.g. mountains and water bodies) is an important factor that results in differences in actual climate changes in specific locations compared to generalized model results.

Climate Patterns and Oscillations

Patterns and oscillations in climate systems are increasingly understood as part of a large interconnected system. The timing and behavior of these patterns is of importance because of their influence on weather. The impact of increasing global average temperatures on these patterns is not fully understood.

Perhaps the most well-known of the patterns is an oscillation in the Pacific Ocean known as ENSO or El Niño Southern Oscillation. The links between oscillations and climate change are of concern because warmer conditions caused by global warming may influence patterns in ways

that accentuate the extremes in these naturally occurring phenomena that cause floods and droughts, strong storm events, higher tides, and other impacts.

El Niño-Southern Oscillation and Pacific Decadal Oscillation

El Niño-Southern Oscillation
El Niño is notorious worldwide for causing catastrophic disruptions in weather patterns. Floods in California are countered by droughts in Australia. El Niño (ENSO) is characterized by a large scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean. El Niño events occur irregularly at intervals of two to seven years, although the average is about once every three to four years. They typically last 12 to18 months, and are accompanied by swings in the Southern Oscillation (SO), an interannual see-saw in tropical sea level pressure between the eastern and western hemispheres. During El Niño, unusually high atmospheric sea level pressures develop in the western tropical Pacific and Indian Ocean regions, and unusually low sea level pressures develop in the southeastern tropical Pacific. SO tendencies for unusually low pressures west of the date line and high pressures east of the date line have also been linked to periods of anomalously cold equatorial Pacific sea surface temperatures sometimes referred to as La Niña.

The Southern Oscillation Index (SOI), defined as the normalized difference in surface pressure between Tahiti, French Polynesia, and Darwin, Australia, is a measure of the strength of the trade winds, which have a component of flow from regions of high to low pressure. High SOI (large pressure difference) is associated with stronger than normal trade winds and La Niña conditions, and low SOI (smaller pressure difference) is associated with weaker than normal trade winds and El Niño conditions.

Pacific Decadal Oscillation
The Pacific Decadal Oscillation, as its name implies, is a longer lived phenomenon, often described as an El Niño-like pattern of Pacific climate variability.[34] Typical PDO "events" have shown remarkable persistence relative to ENSO events—in the 20th century, major PDO eras have persisted for 20 to 30 years. The evidence indicates there have been just two full PDO cycles in the 20th century: cool PDO regimes prevailed from 1890-1924 and again from 1947-1976, while warm PDO regimes dominated from 1925-1946 and from 1977 through (at least) the mid-1990s.[35]

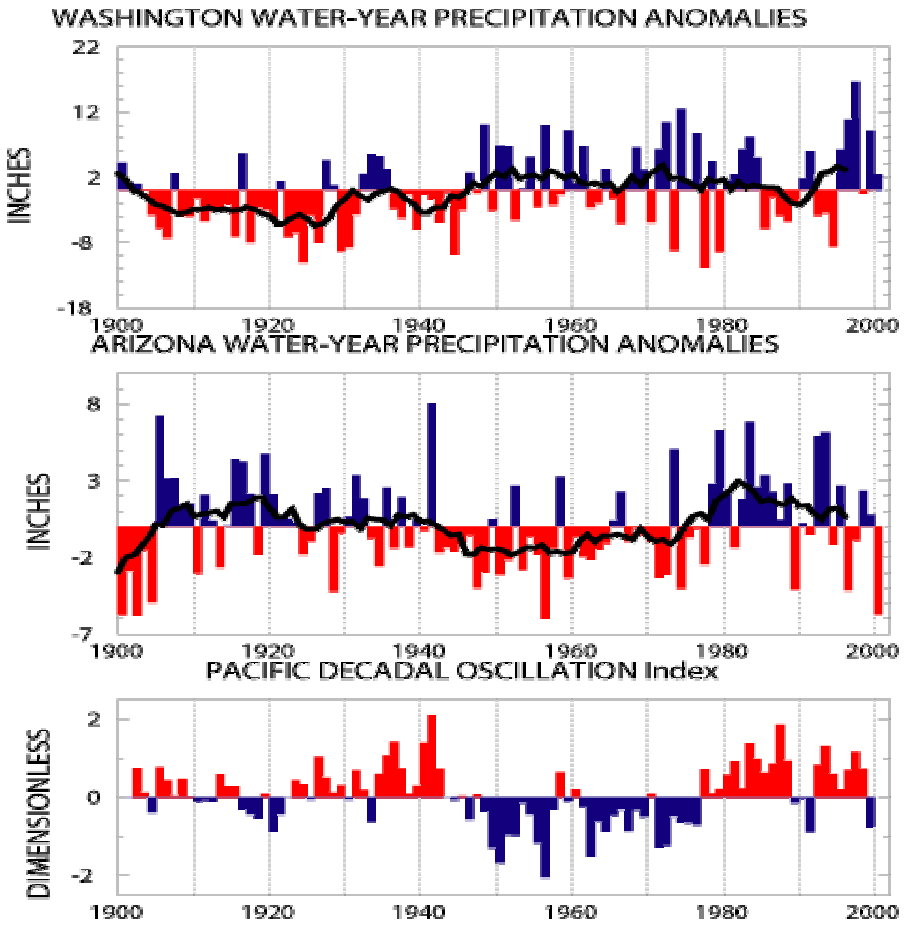
The sea surface temperature (SST) pattern highlights the strong tendency for temperatures in the central North Pacific to be anomalously cool when SSTs along the coast of North America are unusually warm, and vice-versa.[36] Warm phases of the PDO are correlated with North American temperature and precipitation anomalies similar to those correlated with El Niño: above average winter and spring temperatures in northwestern North America, below average temperatures in the southeastern U.S., above average winter and spring rainfall in the southern U.S. and northern Mexico, and below average precipitation in the interior Pacific Northwest and Great Lakes regions. Cool phases of the PDO are simply the reverse climate patterns over North America, broadly similar to typical La Niña climate patterns.[37] The PDO-related temperature and precipitation patterns are also strongly expressed in regional snow pack and stream flow anomalies, especially in western North America.[38] The archetypical El Niño and La Niña patterns are only valid during years in which ENSO and PDO extremes are "in phase" (i.e.: with warm PDO+El Niño, and cool PDO+La Niña).[39]

Sources: National Climatic Data Center. *California Climate Summary*. April 2001. (http://www.ncdc.noaa.gov/ol/climate/research/cag3/CA.html) U.S. Dept. of Commerce/National Oceanographic and Atmospheric Administration. (http://www.pmel.noaa.gov/toga-tao/ensodefs.html)
Mantua, Nathan. "The Pacific Decadal Oscillation and Climate Forecasting for North America." (http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm)

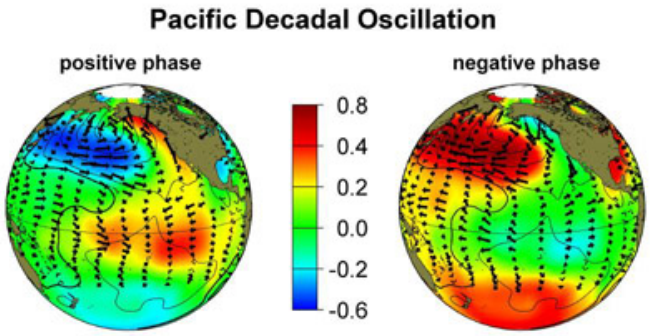
Just as with ENSO, when PDO is in its positive or El Niño-like phase, the southwest is wetter than normal on the whole and the northwest is dry. And just as with ENSO, California is caught in between. The consequence historically has been that California is not necessarily wetter or

drier than normal during every El Niño, but rather that, during some El Niños, it is wetter and, during other, it is drier. Similarly, the influence of PDO on California precipitation is variable. Presumably, just as ENSO contributes importantly to the variability of California's precipitation, PDO does as well.[40]

The following plot developed by Michael Dettinger at USGS illustrates the role of PDO in long-term wet vs. drought cycles in the western States.



Source: Schmidt, K.M., and Webb, R.H., 2001, Researchers consider U.S. Southwest's response to warmer, drier conditions: EOS, v. 82, p. 475, 478. Plot by Michael Dettinger, USGS.



Source: CalTech Jet Propulsion Laboratory (Dr. William Patzert)

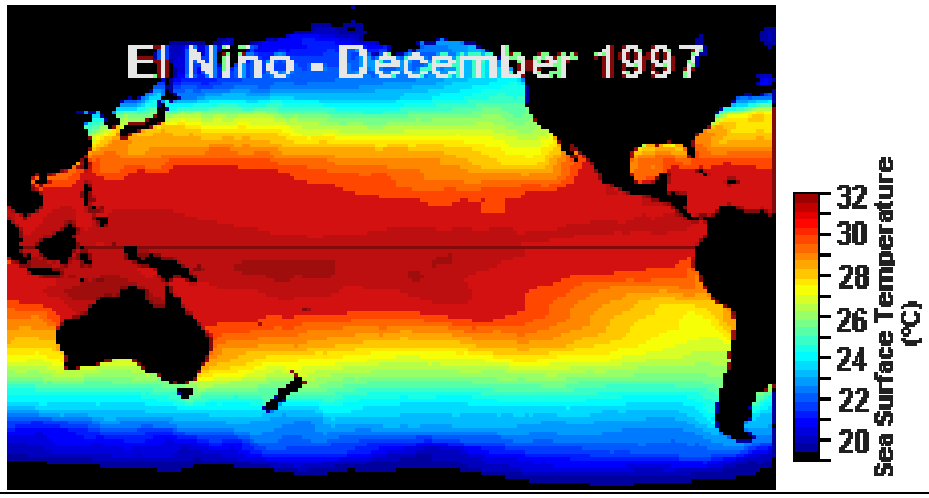
El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) in the Pacific Ocean has a profound impact on weather in California. ENSO events capture public attention when extreme weather hits the state. The frequency and intensity of ENSO may be influenced by increased global temperatures, although there is debate over the direct effects of global warming. This section provides a summary of the ENSO process as background for the California assessment. Further research will provide a better understanding of the relationship between climate change and ENSO.

El Niño Southern Oscillation

Mark Svoboda
National Drought Mitigation Center
University of Nebraska-Lincoln

This section on ENSO is based on an good summary by Mark Svoboda at the National Drought Mitigation Center at the University of Nebraska-Lincoln and information from the National Oceanographic and Atmospheric Administration (NOAA) and other research.[41] References to further information are provided.



NOAA: http://www.pmel.noaa.gov/tao/elnino/la-nina-story.html

El Niño Defined

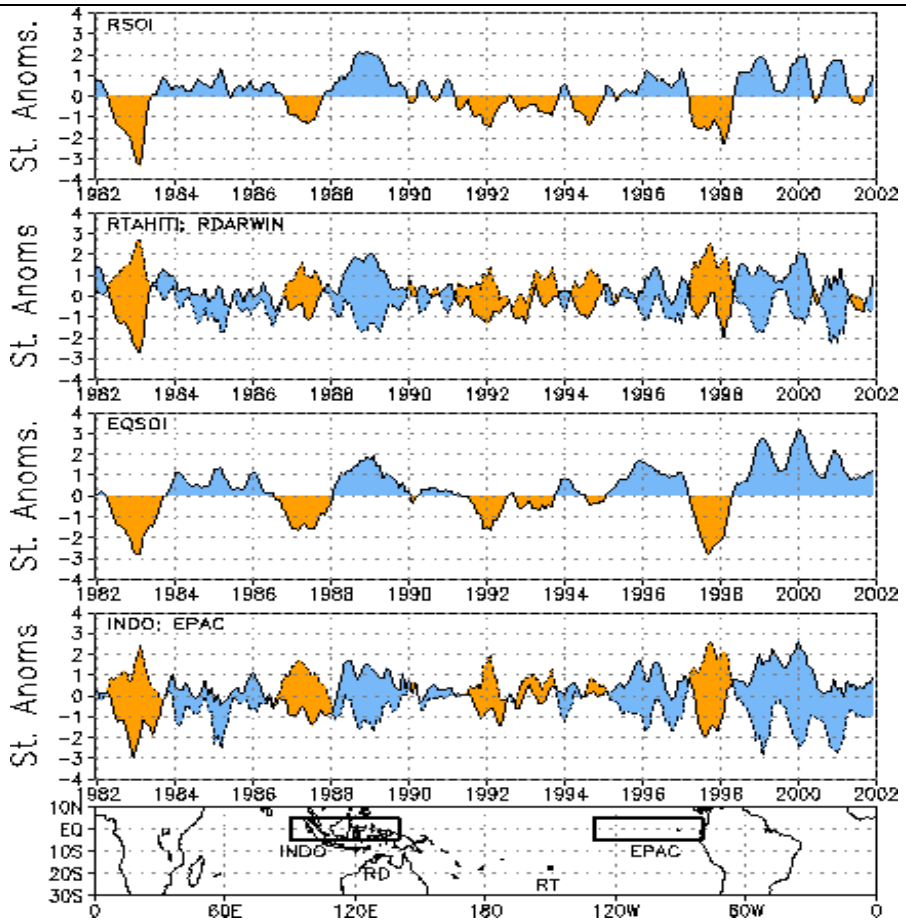
Every two to seven years off the western coast of South America, ocean currents and winds shift, bringing warm water westward, displacing the nutrient-rich cold water that normally wells up from deep in the ocean. The invasion of warm water disrupts both the marine food chain and the economies of coastal communities that are based on fishing and related industries. Because the phenomenon peaks around the Christmas season, the fishermen who first observed it named it "El Niño" ("the Christ Child"). In recent decades, scientists have recognized that El Niño is linked with other shifts in global weather patterns. (For a colorful look at El Niño with real-time graphics, check out NOAA's TAO Project pages at http://www.pmel.noaa.gov/tao/.)

Frequency

The return period of the El Niño event is varied, ranging from two to seven years. The intensity and duration of the event are also varied and hard to predict. Typically, it lasts anywhere from 14 to 22 months, but it can be much longer or shorter. El Niño often begins early in the year and peaks between the following November and January, but no two events behave in the same way. El Niño is by no means a new phenomenon and researchers are still working to determine whether global warming would intensify or otherwise effect El Niño. Evidence of the events goes back hundreds of years. This "proxy," or indirect, climatic data can be found in the form of tree ring analysis, sediment or ice cores, coral reef samples, and even historical accounts from early settlers.

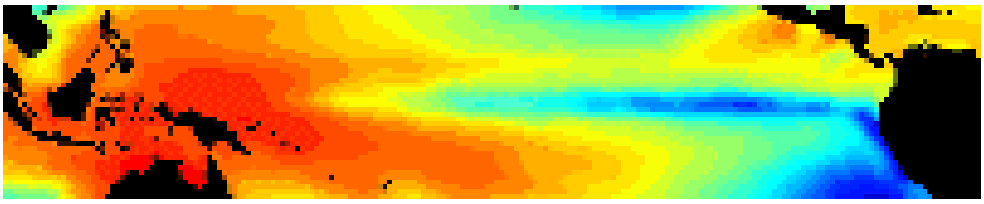
The Southern Oscillation

The Southern Oscillation, "a seesaw of atmospheric pressure between the eastern equatorial Pacific and Indo-Australian areas" (Glantz et al., 1991), is closely linked with El Niño. During an El Niño-Southern Oscillation (ENSO) event, the Southern Oscillation is reversed. Generally, when pressure is high over the Pacific Ocean, it tends to be low in the eastern Indian Ocean, and vice versa (Maunder, 1992). It is measured by gauging sea-level pressure in the east, at Tahiti, and in the west, at Darwin, Australia, and calculating the difference. This is then put into an index which is called the Southern Oscillation Index (SOI) or Tahiti-Darwin Index. High negative values of the SOI represent an El Niño, or "warm event." ENSO events are those in which both a Southern Oscillation extreme and an El Niño occur together. El Niño and Southern Oscillation often occur together, but also happen separately. An example of the SOI from the Climate Prediction Center follows.

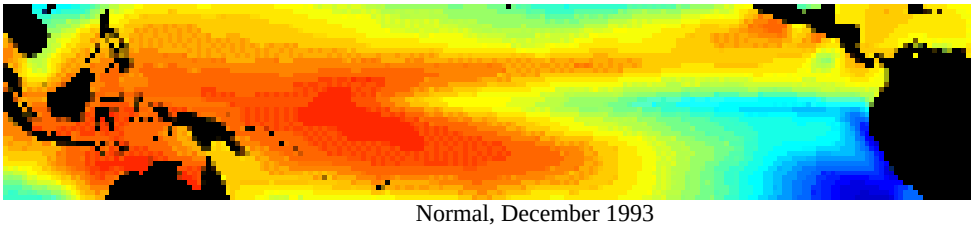


NOAA, http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/bulletin/figt2.gif

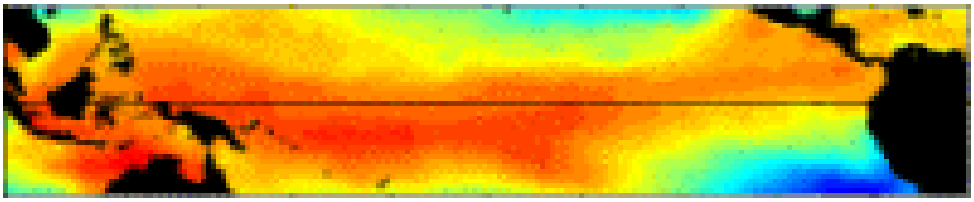
High positive values of the SOI indicate a La Niña, or "cold event." La Niña is the counterpart of El Niño and represents the other extreme of the ENSO cycle. In this event, the sea surface temperatures in the equatorial Pacific drop well below normal levels and advect to the west while the trade winds are unusually intense rather than weak. La Niña years often (but not always) follow El Niño years.



La Nina, December 1998
NOAA: http://www.pmel.noaa.gov/tao/elnino/la-nina-story.html

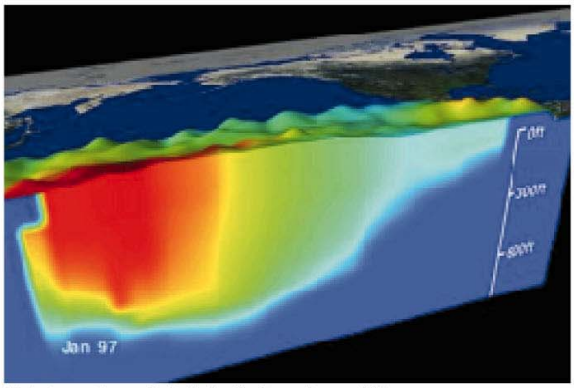


Normal, December 1993
NOAA: http://www.pmel.noaa.gov/tao/elnino/la-nina-story.html

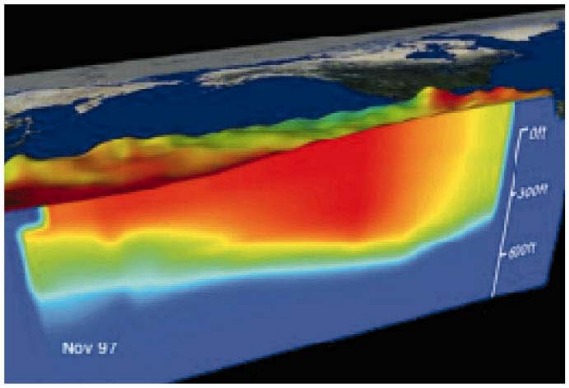


El Nino, December 1997
NOAA: http://www.pmel.noaa.gov/tao/elnino/la-nina-story.html

A three dimensional perspective is provided by the following cut-away views.



Water temperature profile in the Pacific Ocean, January 1997.

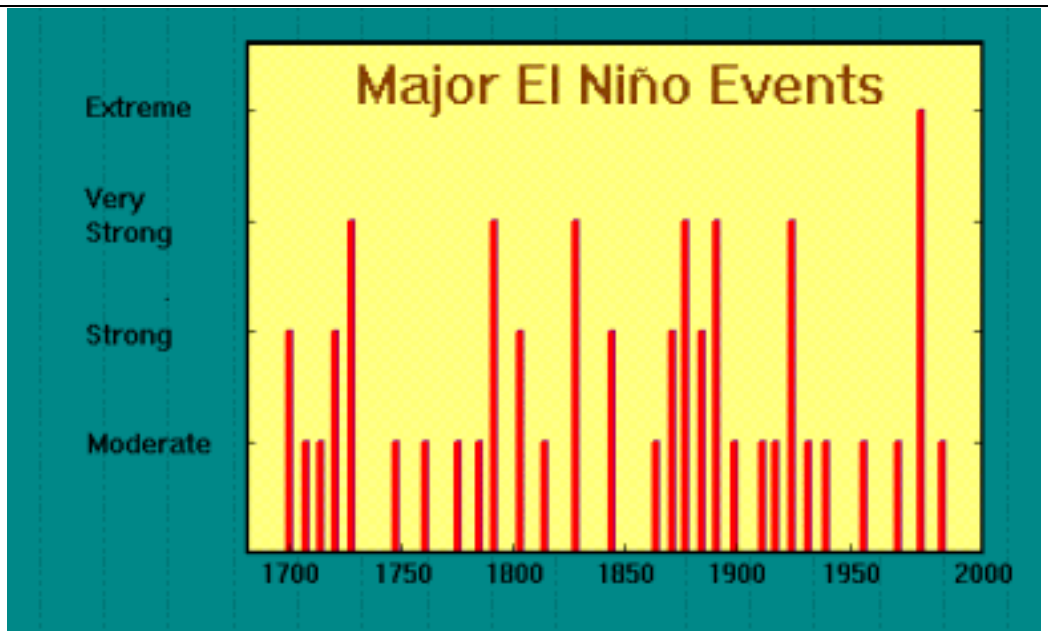


Water temperature profile in the Pacific Ocean, November 1997.

During El Niño conditions, the equatorial pool of warm water (shown in red) expands and moves eastward to span the entire equatorial Pacific east of the dateline. This dramatic warming affects global atmospheric circulation including effects on the jet stream, winter storms, and tropical storms.

Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

A table listing the El Niño and La Niña events since the turn of the century can be found at http://www.umassd.edu/Public/People/Kamaral/thesis/ElNinoYears.html, and a graph of major El Niño events since 1700 from the Earth Space Research Group (ESRG) follows.



http://www.crseo.ucsb.edu/geos/gif/15.gif

"ENSO" is perhaps a better term than "El Niño" for purposes of understanding global weather patterns, as it turns out that the shifts in sea surface temperatures (SST's) off the west coast of South America are just one part of the coupled interactions of atmosphere, oceans, and land masses. The term Southern Oscillation refers to the atmospheric component of the relationship and El Niño represents the oceanic property in which sea surface temperatures are the main factor.

Teleconnections

ENSO occurrences are global climate events that are linked to various climatic anomalies. Not all anomalies, even in ENSO years, are due to ENSO. In fact, statistical evidence shows that ENSO can account at most for about 50% of the interannual rainfall variance in Eastern and Southern Africa (Ogallo, 1994), but many of the more extreme anomalies, such as severe droughts, flooding and hurricanes, have strong teleconnections to ENSO events. Teleconnections are defined as atmospheric interactions between widely separated regions (Glantz, 1994). Many researchers are studying the relationships between ENSO (and La Niña) events and weather anomalies around the globe to determine whether links exist. Understanding these teleconnections can help in forecasting droughts, floods, and tropical storms (hurricanes).
The economic impacts of the 1982-83 El Niño, perhaps the strongest event in recorded history, conservatively exceeded $8 billion world-wide, from droughts, fires, flooding and hurricanes (NOAA, 1994). Virtually every continent was affected by this strong event. Some 1000-2000 deaths have been blamed on the event and the disasters that accompanied it. A list of the effects of the 1982-83 ENSO is available at http://enso.unl.edu/ndmc/enigma/tab1enso.htm. Incidentally, the extreme drought in the Midwest Corn Belt of the United States during 1988 has been inconclusively linked to the "cold event," or La Niña, of 1988 that followed the ENSO event of 1986-87.

ENSO and U.S. Droughts

In North America, particularly the United States, the impacts of El Niño are most dramatic in the winter. El Niño produces winters that are generally mild in the northeast and central U.S. and wet over the south from Florida to Texas. Alaska and the northwestern regions of Canada and the United States can be abnormally warm. This might

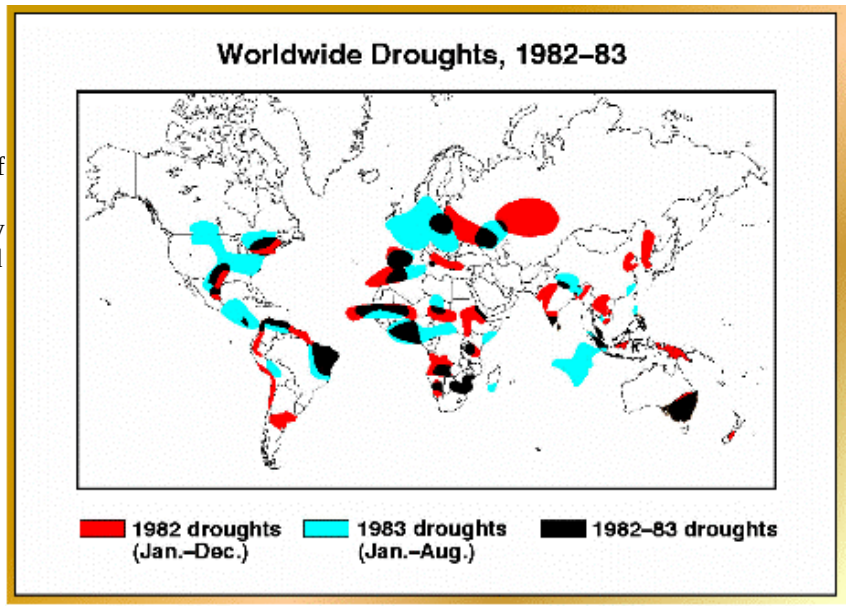
be a result of the forcing due to a Pacific-North American (PNA) pattern that is typified by a high pressure ridge over northwestern North America and a low pressure trough in the southeastern United States. This serves as an upper level steering mechanism for moisture and temperature at the surface. Once the pattern is entrenched, regions under the ridge can expect little in the way of precipitation and those in the trough can't turn it off and are prone to frequent flooding.

Ropelewski and Halpert (1986) studied North American precipitation and temperature patterns associated with ENSO conditions and concluded the following. In the Great Basin area of the western United States, above normal precipitation was recorded during ENSO years in 81% of the cases for the "season" that runs from April to October. In the southeastern United States and northern Mexico, above normal precipitation was also recorded for 81% of the cases for the "season" that began in October of the ENSO year and concluded in March of the following year. For temperature anomalies during ENSO conditions in North America, the Pacific Northwest in the U.S., western Canada and parts of Alaska showed warmer temperatures in 81% of the years while the southeastern U.S. showed below normal temperatures around 80% of the time. This would seem consistent with a typical PNA atmospheric pattern. During stronger events, the United States experiences flooding and severe storms in some regions, and droughts and heat waves in other areas. Hurricane activity is usually minimal in the Atlantic Ocean, sparing the coastal areas from the Gulf of Mexico to the northeast. In the coastal west, the displacement of the jet stream can bring abnormally large amounts of rain and flooding to California, Oregon and Washington. During the summer, heat waves and below-normal precipitation bring drought, crop failures, and even death. U.S. crop losses from the 1982-83 El Niño were projected to be in the neighborhood of $10-12 billion (Wilhite et al., 1987).

ENSO and Drought Around the World

During an ENSO event, drought can occur virtually anywhere in the world, though researchers have found the strongest connections between ENSO and intense drought in Australia, India, Indonesia, The Philippines, Brazil, parts of east and south Africa, the Western Pacific Basin Islands (including Hawaii), Central America, and various parts of the United States. Drought occurs in each of the above regions at different times (seasons) during an event and in varying degrees of magnitude.

Ropelewski and Halpert also looked at the link between ENSO events and regional precipitation patterns around the globe (1987). Northeastern South America from Brazil up to Venezuela shows one of the strongest relationships. In 17 ENSO events, this region had 16 dry episodes. It is not uncommon to find the rain forests burning during these dry periods.



Other areas from their study also showed a strong tendency to be dry during ENSO events. In the Pacific basin, Indonesia, Fiji, Micronesia, and Hawaii are usually prone to drought during an event. Virtually all of Australia is subjected to abnormally dry conditions during ENSO events, but the eastern half has been especially prone to extreme drought. This is usually followed by bush fires and a decimation of crops. India has also been subjected to drought through a suppression of the summer monsoon season that seems to coincide with ENSO events in many cases. Eastern and southern Africa also showed a strong correlation between ENSO events and a lack of rainfall that brings on drought in the Horn region and areas south of there. One final region they found to be abnormally dry during warm events was that of Central America and the Caribbean Islands.

Thus, there seems to be a stronger influence by ENSO events on regions in the lower latitudes, especially in the equatorial Pacific and bordering tropical areas. The relationships in the mid-latitudes aren't as pronounced nor are they as consistent in the way wet or dry weather patterns are influenced by El Niño. The intensity of the anomalies in these regions is also more inconsistent than those of the lower latitudes. NOAA's Climate Prediction Center has short papers on the typical impacts associated with ENSO and La Niña episodes.[42]

Can We Predict ENSO?

If we can understand some of the teleconnections discussed above, it can lead us to some general predictive capabilities via numeric computer models that can help us determine and conclude when conditions are favorable for the onset of an event. Numeric models try to emulate processes (and dynamic relationships) that occur in nature using sets of numbers and equations. But once an event is underway, forecasting its duration and intensity are difficult at best.
In Ropelewski and Halperts' (1987) study on global precipitation patterns and ENSO events, they found that the consistency and magnitude of the precipitation relationships to ENSO events could serve as a practical utility for forecasting precipitation in certain regions (and seasons) once it was determined that an event was in progress. This can serve as a broad brush approach for given regions with the understanding that expanses within any given area will not behave in the exact same manner from event to event.

NOAA has established and now operates an array of moored buoys in the equatorial Pacific Ocean. These buoys measure temperature, currents, and winds in this region on a daily basis. The data is available to scientists around the world in real time enabling them to use the data for both research and forecasting. This network is very valuable in that the first stages of an ENSO event occur in this region. By monitoring data from past episodes and the data from the months leading up to an episode, scientists can use numerical models (similar, but not as reliable, to those used in weather forecasting) to help them predict and/or simulate ENSO events. The predictive models are becoming more sophisticated and more effective in many respects thanks in part to the expanded data sets that are available for the equatorial Pacific region. The dynamic coupled nature of the new models has allowed for prediction of ENSO events a year or more in advance.

ENSO forecasts help countries anticipate and mitigate droughts and floods, and are very useful in agricultural planning. Countries such as Brazil, Australia, India, Peru and various African nations that are in latitudes with strong El Niño connections to weather patterns, use predictions of near-normal conditions, weak El Niño conditions, strong El Niño conditions, or a La Niña to help agricultural producers select crops most likely to be successful in the coming growing season. In countries or regions with a Famine Early Warning System (FEWS) in place, ENSO forecasts can play a key role in mitigating the impacts of flood or drought that can lead to famine. Famine, like drought, is a slow-onset disaster, so forewarning may enable countries to greatly reduce, if not eliminate, its worst impacts.

ENSO advisories are used to a lesser extent in planning in North America and other extratropical countries, because the links between ENSO and weather patterns are less clear here. As prediction models improve, the role of ENSO advisories in planning in mid-latitude countries will increase. The Climate Prediction Center is responsible for issuing ENSO advisories. For the latest information on the status of ENSO, go to the ENSO Diagnostic Advisory at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/index.html.

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WWW Resources:

Climate Prediction Center's El Niño/La Niña Home Page, http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/lanina/

NOAA/PMEL/TAO's El Niño Theme Page, http://www.pmel.noaa.gov/tao/elnino/nino-home.html

Climate Diagnostics Center's El Niño Analysis and Predicition, http://www.cdc.noaa.gov/ENSO/

El Niño in the Western United States, Alaska, and Hawaii, http://www.wrcc.sage.dri.edu/enso/enso.html

USA Today's El Niño Information Page, http://www.usatoday.com/weather/nino/wnino0.htm

North American Climate Patterns Associated with El Niño-Southern Oscillation, http://www.coaps.fsu.edu/lib/booklet/

NOAA's Office of Global Programs El Niño Page, http://www.ogp.noaa.gov/enso/

Ocean Planet, http://seawifs.gsfc.nasa.gov/OCEAN_PLANET/HTML/oceanography_el_nino.html

Sea Level Change

Sea levels fluctuate over geologic time scales due both to changes in climate and to movements of land areas. During “ice ages” when large amounts of water are stored in ice and snow, sea

levels drop. As this stored water melts, sea levels rise. Thermal expansion also affects the sea level. The coastal sector report explains that:[43]

> On average, global sea-levels have been gradually rising since the conclusion of the last ice age approximately 15,000 years ago; although rates over the last 6,000 years have fluctuated somewhat. During the last 100 years, sea-level rise has occurred at a rate of approximately 1 to 2 millimeter per year, or 10 to 20 centimeters (4 to 8 inches) per century, according to most estimates.[44] This refers to the eustatic sea-level, the absolute elevation of the earth's ocean, which has been determined from tidal stations around the globe.
>
> However, there are large regional variations due to subsidence, isostatic (glacial) rebound, tectonic uplift, and other factors that contribute to a "relative" sea-level rise which usually differs from the global average. While some long-term tide-gauge records suggest that there may have been a slight increase in the rate of sea-level rise observed over the last century, efforts to verify this have generally been unable to confirm a significant acceleration.[45]

Sea levels are also influenced on shorter time scales by various factors.

Sea-Level Change

The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources [46]

Coastal water levels rise and fall on various time scales. Tides resulting from the gravitational attraction of the sun and moon cause water levels to rise and fall daily anywhere from a few centimeters in some estuaries to four meters along the Gulf of Maine. The amplitude of the daily tide fluctuates by about one-third twice each lunar month, according to whether the solar and lunar tides are in phase with each other. Storm surges, winds, currents, rainfall and other factors can also affect water levels on short time scales. These effects are significant because many of the expected impacts associated with sea-level rise are the result of the increase in the baseline sea-level for storm surges and flooding events, rather than direct effects of sea-level rise itself.

Generally, sea-level refers to the average water level over the course of a 20-year period, which is enough time for astronomic and most climatic fluctuations to run through their complete cycles (such as the cycling of Perigean spring tides).[47] Over geological time scales however, sea-level has fluctuated greatly. During the Cretaceous Period, over 100 million years ago, sea-level was as much as 350 meters above present levels,[48] corresponding with a time of rapid seafloor spreading, an ocean between 10 and 15°C warmer than today's, and a warmer atmosphere with little or no landlocked ice. More recently, sea-level has risen and fallen with the 100,000-year glacial-interglacial cycle. During glacial periods, sea-level has been as much as 120 meters (nearly 400 feet) lower than current levels,[49] whereas during the warmer interglacial periods, sea-level has been as much as 5 to 7 meters (about 20 feet) higher than the present.

Thermal expansion and the storage of water in snow and ice are the two primary causes of sea level change over a time scale of several thousand years. In the next century, thermal expansion is expected to be the major driver.[50]

> Most of the sea-level change observed over the last several hundred thousand years is accounted for by two major variables; the thermal expansion or contraction of the oceans (steric effects) and the amount of water that is locked up in glaciers and ice sheets. The thermal component results from expansion and contraction of the volume of the ocean associated with changes in mean ocean temperatures; given an equal mass the total volume decreases when ocean temperatures drop, and expands when temperatures increase. Gornitz reviewed a number of assessments of estimated contributions to sea-level rise, which generally suggested that the majority of sea-level rise anticipated over the next century is likely to result from thermal expansion of the oceans.[51]

In addition to land movement, various climate factors affect sea level.[52]

> Land movements are not, however, the only reason for regional variations in the rate of sea-level rise. Regional climate can also alter sea-levels through changes in local atmospheric pressure and alongshore wind stress, integrated water column density and thermocline depth.[53] Variability in short-term average sea-level can also be significant; for example, along the west coast of the Americas relative sea levels may increase during strong El Niño events by as much as 20 to 50 centimeters (7 to 20 inches) over short time periods.[54] Additionally, Ruggiero et al. found increased short-term sea-levels along the Oregon coastline corresponding with major El Niño events between 1970 and 1995.[55]

The Canadian and Hadley models project different sea level conditions due in part to wind patterns and currents.[56]

> In general, the Hadley model predicts a greater sea-level rise for the Pacific coast than for the Atlantic and Gulf coasts as a result of altered current and wind patterns. By contrast, the Canadian model predicts a more complex pattern of sea-level rise, but with relatively similar increases along all U.S. coasts.
>
> The Canadian climate model predicts an increase in the Pacific North American Index (PNA, based on sea-level pressure measurements in the North Pacific) over the next century, particularly after 2050. The Hadley model, however, predicts a generally lower PNA index in the latter part of the next century, although it does produce a strengthening and southward shift of the Aleutian Low by 2090. A climate index based on water temperature patterns over the North Pacific (the Pacific Decadal Oscillation, or PDO Index) is projected to increase in the both the Canadian and Hadley models with a stronger trend in the former.
>
> The second major consideration for wind-driven processes involves intensity of upwelling and downwelling processes. The trade winds drive surface waters away from the west coasts of North and South America and these surface waters

are replaced by deeper nutrient rich waters, resulting in high levels of primary productivity in these upwelling regions. Factors affecting wind fields therefore will affect the intensity of upwelling. Bakun has argued that increased heating over land could exacerbate the differential between land and sea temperatures, leading to increased local winds and therefore increased localized upwelling.[57] In general, heating over land causes increased land/sea temperature gradients during summer months, but the reverse is usually true in the winter. Possible changes in the frequency and intensity of El Niño Southern Oscillation (ENSO) events will also have important consequences for upwelling in the California Current System.[58] The Canadian model shows a steady decrease in the Southern Oscillation Index (SOI; sea-level pressure difference between Darwin Australia and Tahiti). A lower index favors El Niño conditions and therefore more frequent ENSO events are projected under this model. By contrast, the Hadley model shows no clear trend in ENSO events until a quadrupling of atmospheric carbon dioxide concentrations.[59]

Summary

There is general agreement in both the U.S. and international scientific communities that *global warming is occurring* and that *climate change and variability is a serious issue*. This is clearly confirmed by the IPCC and the National Research Council analysis conducted at the request of the White House in 2001.[60] While there remains uncertainty regarding many aspects of climate change, there is broad consensus among scientists that global warming will cause changes in climate systems and that climate change will in turn potentially cause impacts to many critical systems.

Climate changes through time, and research indicates that significant fluctuations in temperature and precipitation have occurred in the past. The scientific research reviewed indicates that the *rate of climate change* is cause for concern. Rapid change and increased variability in climate systems may be particularly challenging for both natural and human systems to adapt to. Some systems may not be able to adapt in time.

The following sections of this assessment examine the California region and the potential implications of climate change and variability.

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III. The California Region

California is one of the most diverse regions – ecologically, geographically, and culturally – of any in the world. This section seeks to outline the basic features of California; its key economic sectors, important physical features, environmental conditions, and diverse population. The potential impacts of climate change and variability to these systems are then explored in the following sections of this assessment.

Introduction: The People and the Place

California's trillion dollar economy is the largest in the nation and would rank fifth largest in the world if it were an independent country.[1] Within the United States, it has the largest population, the greatest diversity of people and environments, and some of the most difficult problems. In many ways, California appears to be a series of contradictions: the state has the most energy-efficient economy in the U.S. but the highest total energy consumption. In 2001, it had a serious energy crisis with both shortages and surpluses in the same year. It has the most automobile-dependent transportation system and the most cars of any state, but the average Californian drives less than the average American.[2] It boasts the most stringent air quality standards, and yet it has among the worst air quality problems. California has both the greatest variety of ecosystems and the largest number of threatened and endangered species in the continental U.S.

The Golden State has been called a land of superlatives. Its physical geography includes the lowest valley in the northern hemisphere, the highest peak in the lower 48 states, the greatest climatic variation, the driest desert in North America, some of the richest agricultural lands, and the most land devoted to parks and wilderness outside Alaska.[3]

California is diverse, dynamic, and powerful, yet the state's complex natural systems and extensive human activities are highly susceptible to climate variability and change. California is subject to a number of natural stresses which can and do negatively affect the state's economy and quality of life. From floods, mudslides, and coastal erosion to droughts, fires, and heat waves, existing climate-induced stresses are quite real. The prospect of *increased* variability in climate patterns should therefore be a major consideration for all Californians in planning the state's future.

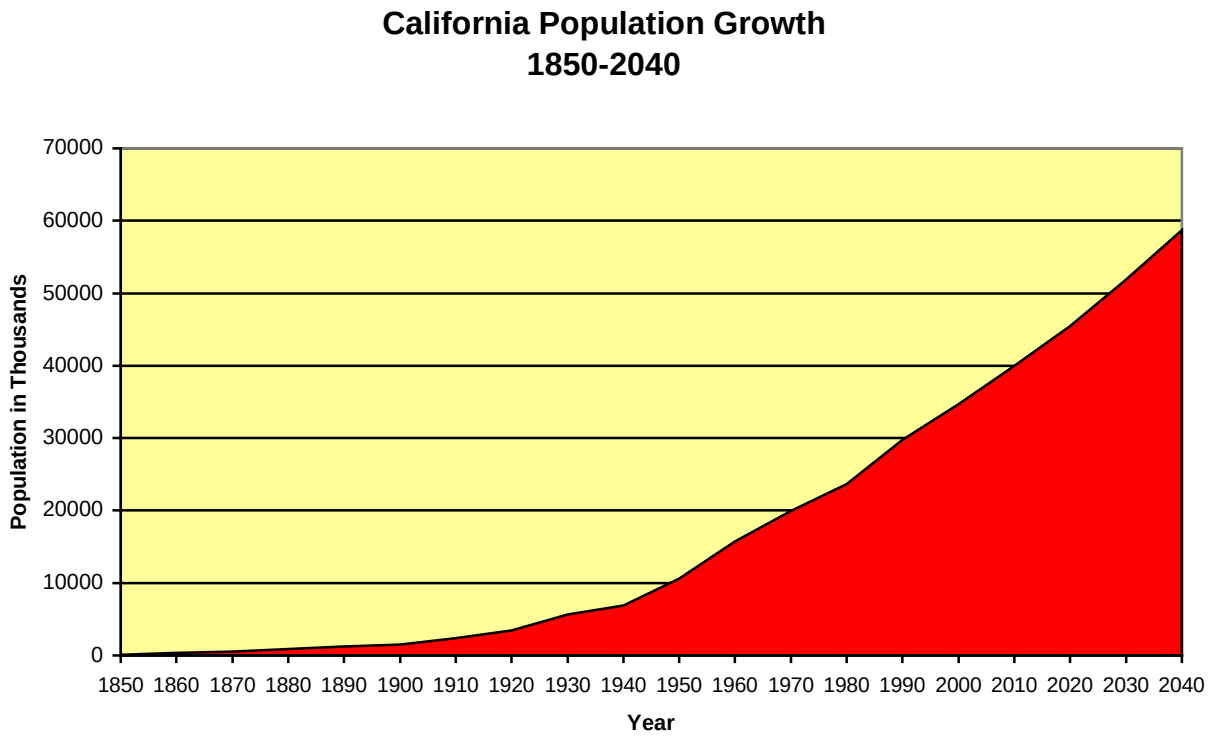
A California Index

Economic[4]	
Gross State Product, 2000:	$ 1.35 trillion
Exports, 2000:	$130 billion
Population[5,6]	
Population, 2000:	33,871,648
Percent change, 1990 to 2000	13.6%
Los Angeles Metro population:	16,373,645
San Francisco Metro population:	7,039,362
Physical Factors and Variation[7]	
Total Land Area:	155,973 square miles
Total Water Area:	7,734 square miles
Total Surface Area:	163,707 square miles
Lowest Valley in Northern Hemisphere:	Death Valley, 282 ft. below sea level
Highest Mountain in Contiguous U. S.:	Mt. Whitney, 14,495 ft. above sea level
Climate Extremes[8,9,10, 11,12]	
Average annual rainfall, Eureka	37.53 inches
Average annual rainfall, Imperial	2.75 inches
Average annual rainfall, San Francisco	19.71 inches
Average annual rainfall, Los Angeles	14.77 inches
Maximum recorded temperature: Death Valley, July 10, 1913	134° F
Maximum recorded rainfall in 24 hours San Gabriel Mountains, January 22-23, 1943	26.12 inches
Maximum annual rainfall in the state: Monumental, 1909	153.54 inches
Minimum recorded rainfall: Bagdad, Mojave Desert, from 3 October 1912	767 days

The People of California

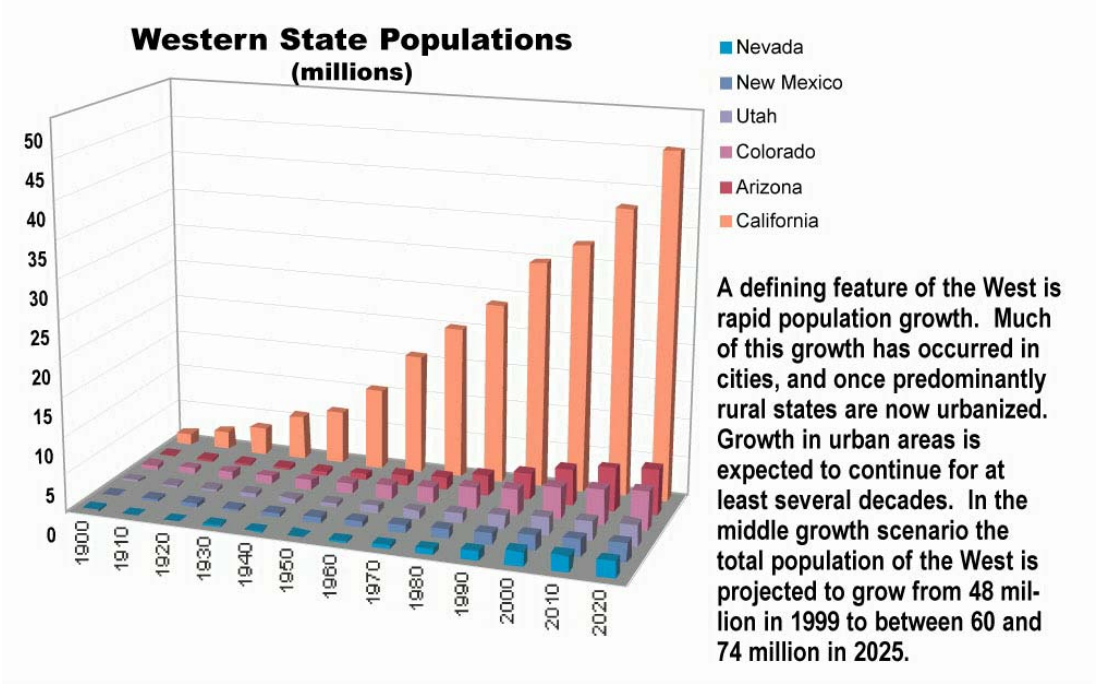
California is both the most populous and most ethnically diverse state in the union. Of the more than 34.5 million residents, 47 percent are white, 32 percent Hispanic, 11 percent Asian and Pacific Islander, 7 percent black, and 0.5 percent Native American. The non-white population now exceeds 53 percent.[13] California is also the fastest growing state according to the 2000 census data.[14]

California's population has more than quadrupled since World War II, mushrooming from less than 7 million in 1940 (about 5 percent of the nation) to 34,385,000 in 2001 (more than 12 percent of the U.S. population).[15] The growth rate over the past decade has fluctuated between 0.9 percent to 2.8 percent.[16] California draws the majority of its immigrants from Mexico, the Philippines, and China, followed by Vietnam, India, El Salvador, and Korea.[17] The projected California population could exceed 49 million in less than 25 years.[18]



California Department of Finance, Historical Population: http://www.dof.ca.gov/html/Demograp/1900-90.htm
Population Projections: http://www.dof.ca.gov/html/Demograp/p1.xls

California's rapid population growth is impacting the entire western United States. As the following graph indicates, the state's absolute numbers and growth rate overshadow all of the other western states combined. As discussed further in this assessment, there are important stresses to various natural and human systems due to the existing population numbers and to the rapid growth rate.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Rates of change are important in many systems. The following table provides a snapshot of California's population growth rate over the past decade with both total population and annual growth figures provided. The population *added in one decade* exceeds the *total population* in large areas of the nation.

California Population Growth 1990–1999

		Growth	
Year	**Population**	**Number**	**Percent**
1990	29,944,000	802,000	2.8
1991	30,565,000	621,000	2.1
1992	31,188,000	623,000	2.0
1993	31,517,000	329,000	1.1
1994	31,790,000	273,000	0.9
1995	32,063,000	273,000	0.9
1996	32,383,000	320,000	1.0
1997	32,957,000	574,000	1.8
1998	33,494,000	537,000	1.6
1999	34,036,000	542,000	1.6

Source: California Statistical Abstract, January 2001. Table B-1.

More than two-thirds of Californians live in the coastal areas of Los Angeles and San Francisco.

Southern California's population (six counties including San Diego County) has climbed to over 19 million:

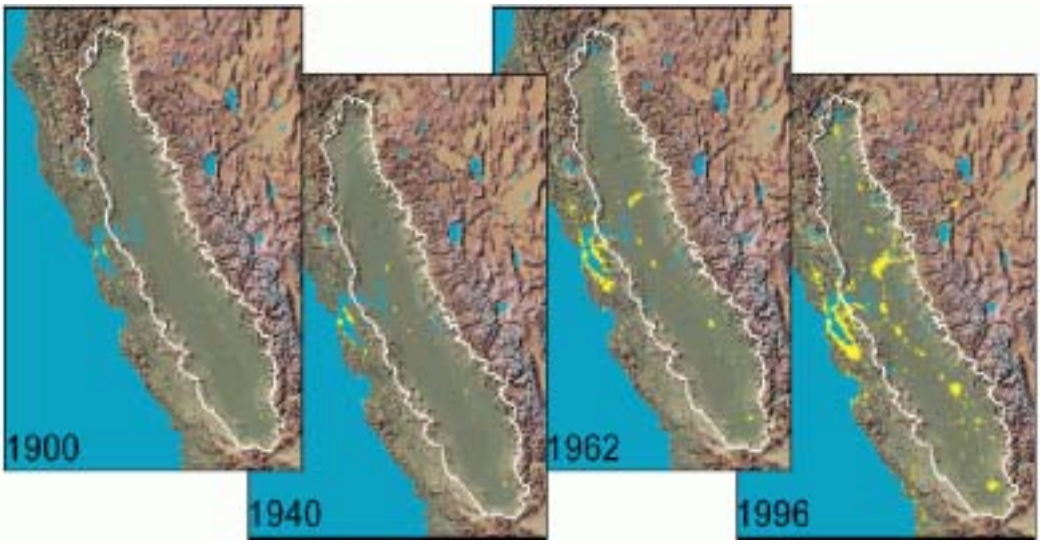
Southern California Population Growth[19]

County	4-1-90	4-1-00
Los Angeles	8,863,052	9,519,338
Orange	2,410,668	2,846,289
Riverside	1,170,413	1,545,387
San Bernardino	1,418,380	1,709,434
San Diego	2,498,016	2,813,833
Ventura	669,016	753,197
6 County Total	17,029,545	19,187,478
State Total	29,758,213	33,871,648

The 10-county San Francisco Bay Area has more than 7 million people.[20] California has among the highest median home prices in the nation[21] and, not surprisingly, has a homeownership rate of only 55 percent.[22] Much of the state's most valuable real estate is located on slopes and in coastal areas which are susceptible to climate impacts. Much of the state's development is now occurring in inland areas. The Central Valley in particular is experiencing rapid growth.

The following images from USGS provide a series of snapshots through the century of the growing urbanization of the San Francisco Bay area and the Central Valley.

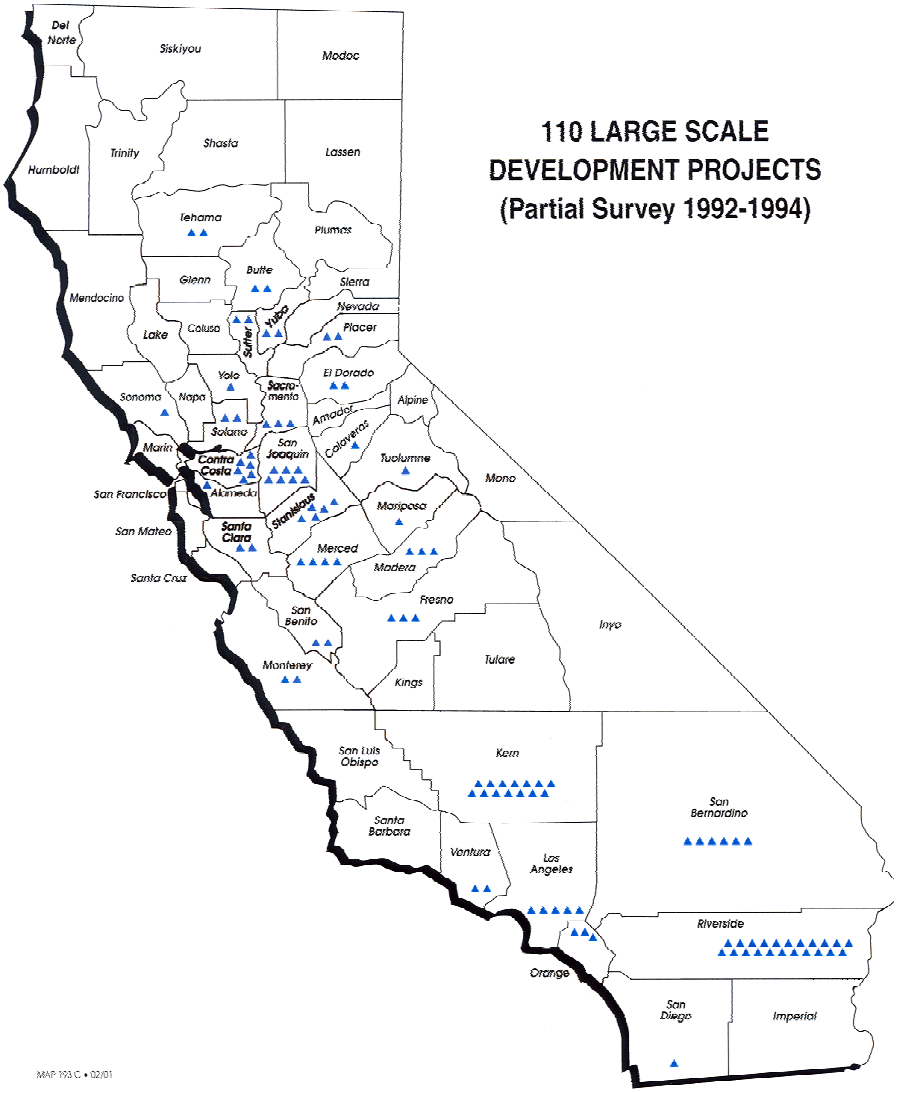
Urban Growth in the Central Valley

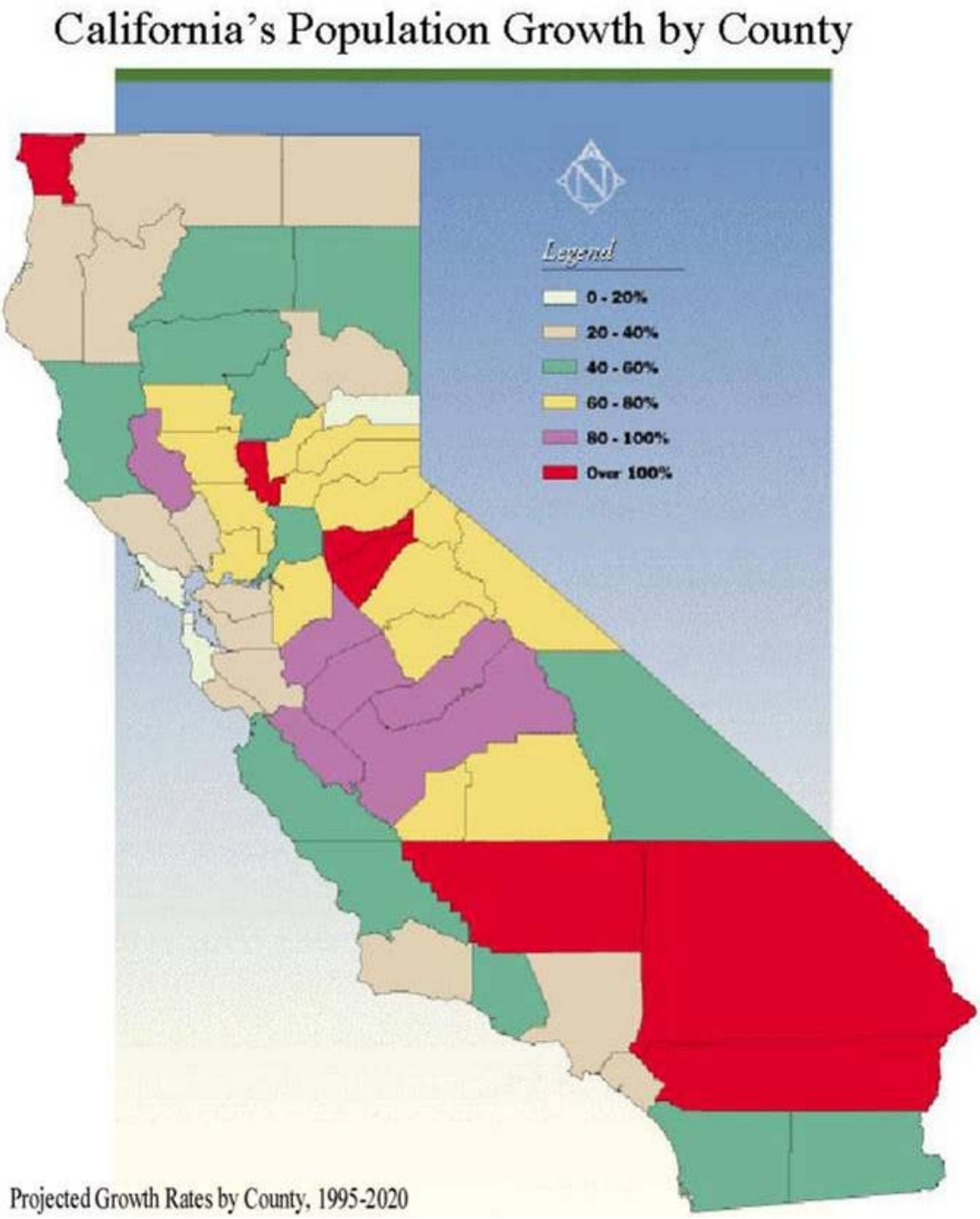


Source: William Acevedo of USGS at NASA/AMES, http://atrs.arc.nasa.gov/r_t/1999/earth/ecosystem6.html

Growth and sprawl have become major issues in the state, as more than 100 "new towns" are planned in the Central Valley and in desert areas in the south.[23] The American Farmland Trust and the California Department of Forestry estimate that between one and two million additional acres will be urbanized in the next decade to accommodate California's population growth.[24] Demands on infrastructure and natural systems, from roads to rivers, is exceeding the carrying capacity of both the built and natural environment. The large population in the state, and the rapid growth rate, place stresses on California in many ways.

110 "New Towns" Planned in California[25]



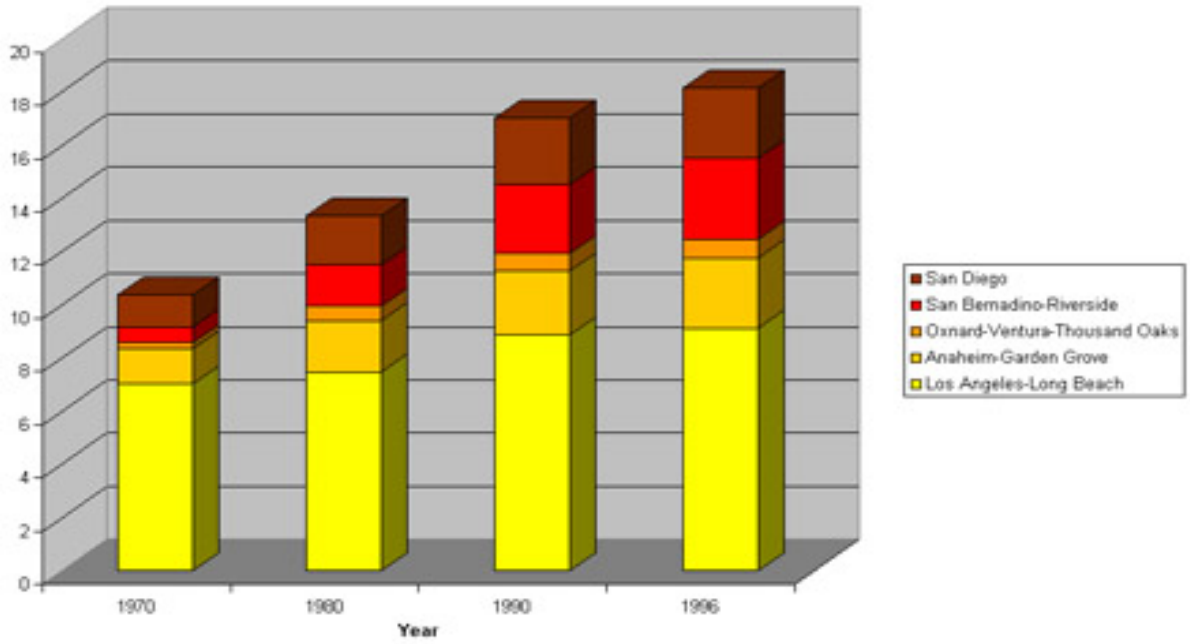


Source: California Department of Finance

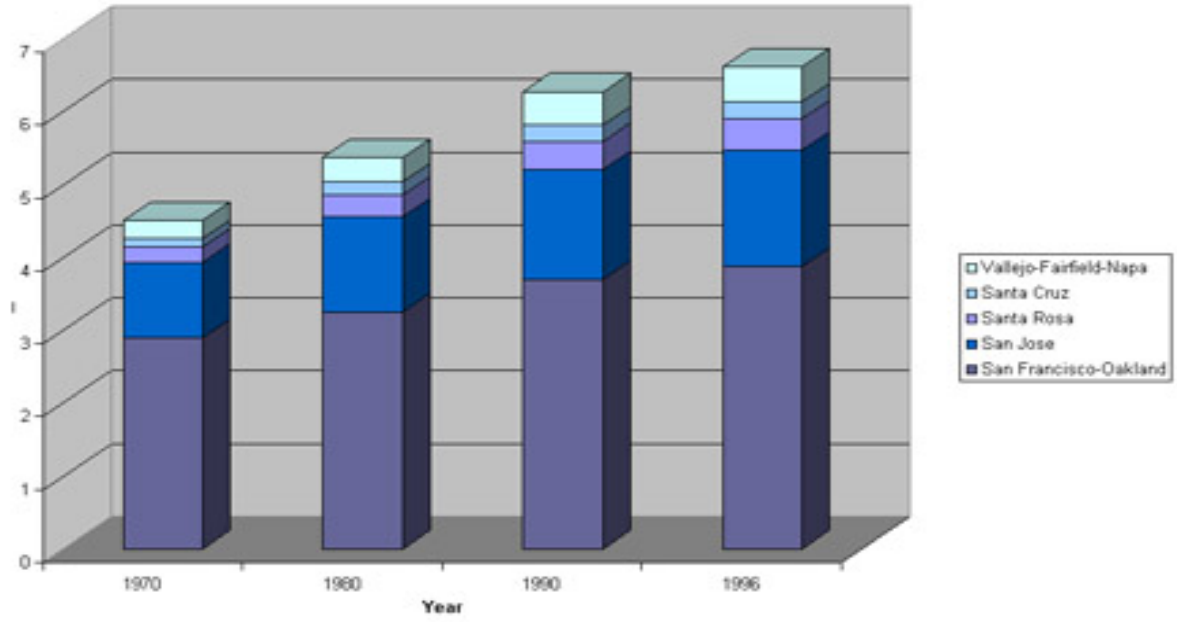
The growing population requires more space in which to live, work, and play, and this expansion into natural habitats—from coastal marshes and bluffs to inland valleys with rich soils to mountain resorts—has placed tremendous pressures on resources, ecosystems, and native plants and animals.

Population Growth 1970-1996
(in millions)

Southern California



Northern California



Source: U.S. Census Bureau

California's Geography and Environment

California stretches nearly 800 miles north to south, covering 163,707 square miles (104.7 million acres).[26] Just over half the state's land is under private ownership. U.S. Government holdings total 46 percent: the U. S. Forest Service owns 21 percent, Bureau of Land Management 17 percent, National Park Service 4.7 percent, Department of Defense 2.8 percent, and the Bureau of Indian Affairs 0.5 percent. Just 2.5 percent is held by the state government. Some 12 million acres are in some type of protected areas—9.4 million in state and national parks—with 6.4 million set aside primarily for the protection of ecological and biodiversity values.

Protected Status and Total Area of California Land Managed by Federal Agencies

UCSB Gap Analysis Project[27]

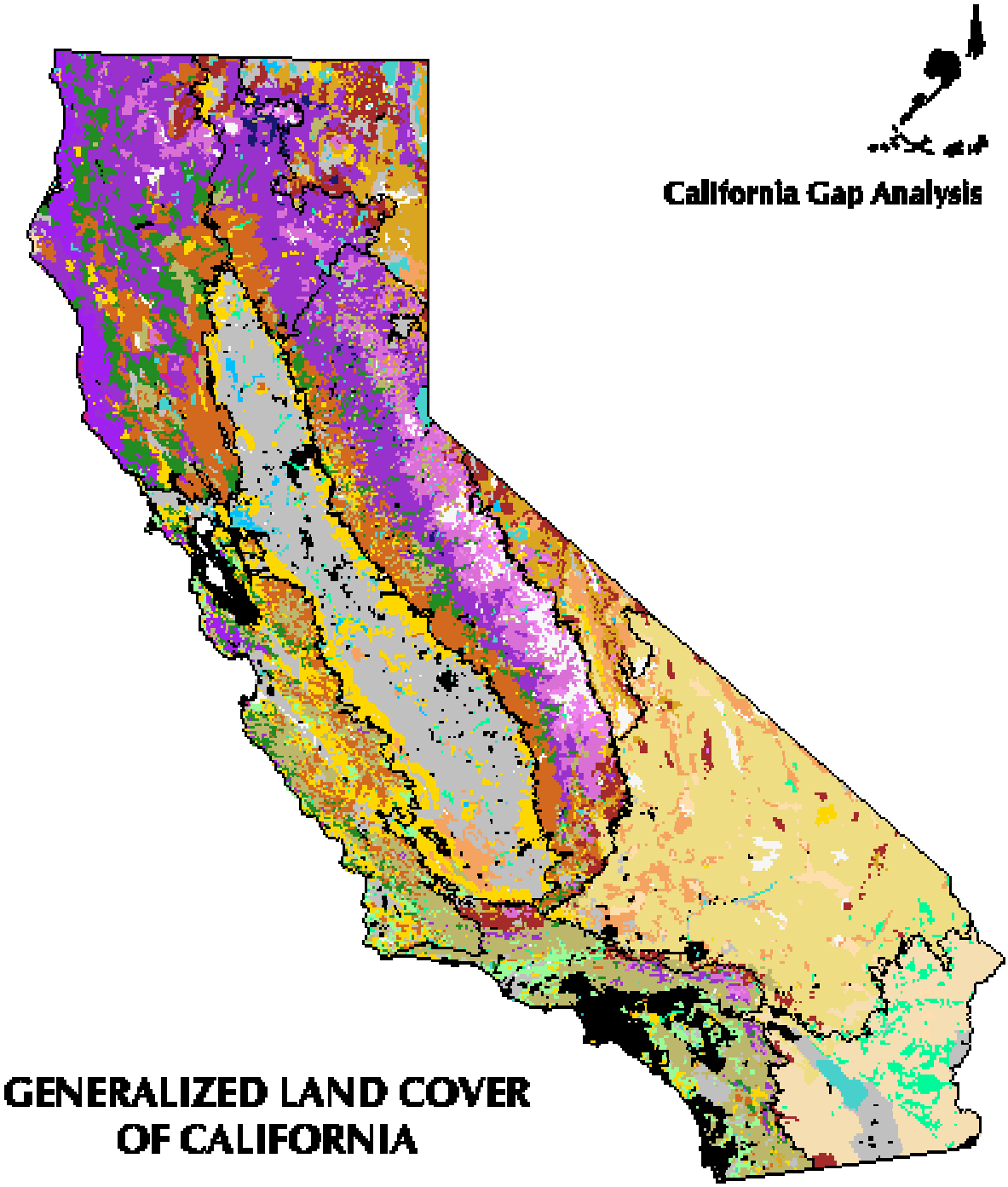
Agency	Acres of Protected Land	Acres of Unprotected Land
National Park Service	7,718,133	2,519
U.S. Bureau of Land Management	4,068,370	10,390,917
U.S. Forest Service	3,911,684	15,758,790
U.S. Fish and Wildlife Service	271,965	0
Military	1,323	4,029,664
NOAA	1,023	0

Protected Status and Total Area of California Land Managed by State Agencies

UCSB Gap Analysis Project[28]

Agency	Acres of Protected Land	Acres of Unprotected Land
Department of Parks and Recreation	1,009,492	153,057
Department of Fish and Game	400,327	883
State Lands Commission	29,014	651,024
Department of Water Resources	2,412	0

As much as 40 percent of the state is subject to livestock grazing.[29] Farms occupy nearly 3 million acres, and of the 16.6 million acres of California's timberlands, 44 percent is held privately.[30]



Source: California GAP Analysis, UCSB.[31]

There is more diversity in the state's land forms, climate, ecosystems, and species than in any comparably-sized region in the nation, and perhaps the world. California has foggy coastal forests, hot low deserts, cold high deserts, forested mountains, alpine glaciers, vast dry valleys, rich agricultural lands, rocky shores, sandy beaches, protected harbors, inland seas, freshwater lakes, and wild rivers.

California's varied climates and complex land forms create a diversity of habitats that cradle an abundance of life forms unmatched in North America. More than 5,000 native plants compose as many as 1,000 distinctive plant communities. There are nearly 1,000 native vertebrate species—540 birds, 214 mammals, 77 reptiles, 47 amphibians, and 83 freshwater fishes—and countless invertebrate species inhabiting the region. About one-third of California's plants are endemic, and as many as half of the animal species are found nowhere else.[32]

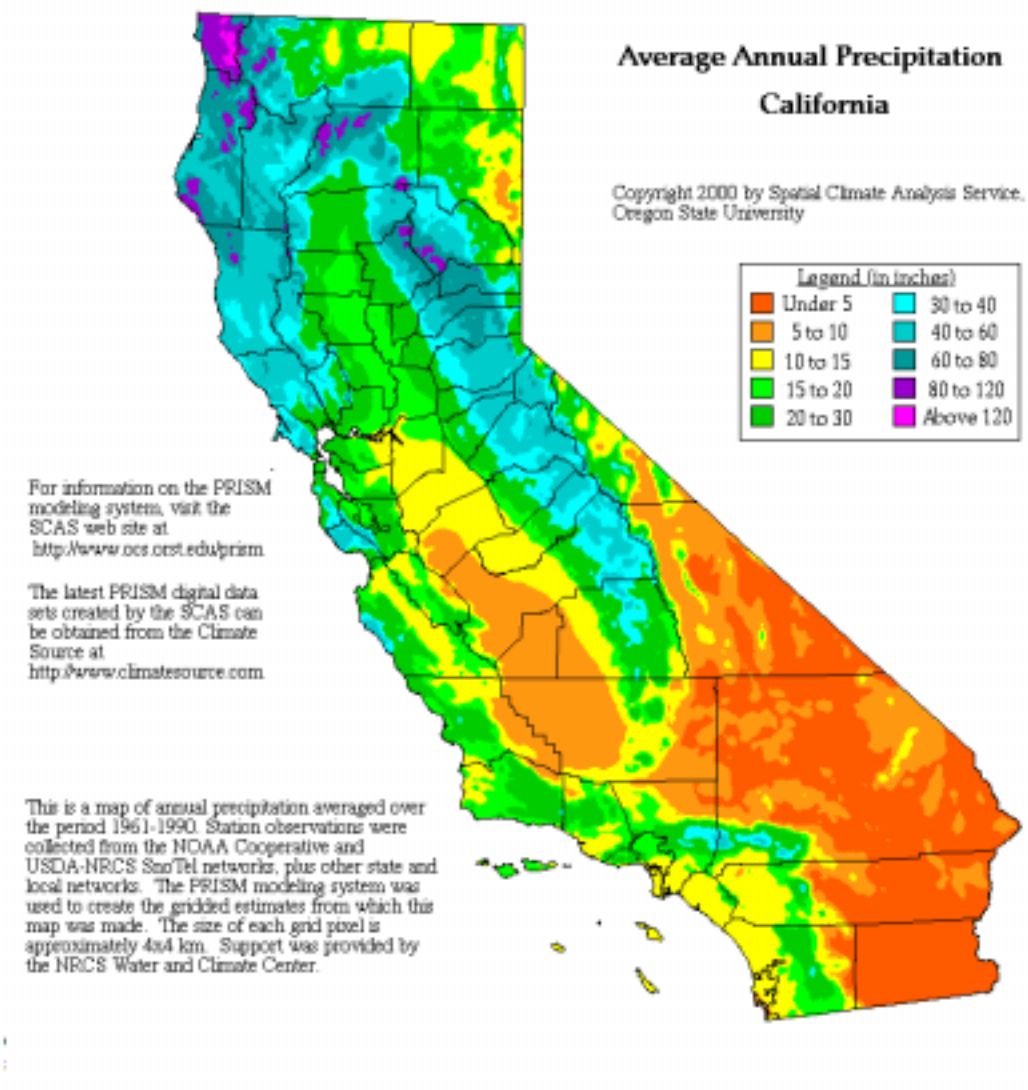
Climate conditions vary dramatically in the state. Much of California is considered to have a mild, Mediterranean climate influenced by the Pacific Ocean, with cool wet winters and warm dry summers. The climate is strongly influenced by the Pacific and its characteristic pressure systems. The location of the Pacific High, a large and relatively stable high pressure area located over the northern Pacific Ocean, is a primary factor in California's rainfall patterns. In summer, the Pacific High moves northward in the eastern Pacific, effectively blocking storms carried southeasterly by the prevailing winds. In winter, the High drifts southward, allowing more storms to hit the state. Because storms come from the northwest and begin releasing moisture as they sweep inland over northern California, the north receives much more rain than the south. As the storms move east across the mountain ranges, almost all of which trend north-south, more rain is released when the systems are forced upslope. This brings substantial rainfall to the coastal ranges and the Sierra Nevada, leaving the valleys to the east in a "rainshadow" with little precipitation.

Climate Variability in Time and Place in California

Precipitation fluctuates greatly from place to place and year to year, however, and floods and droughts are equally legendary. The highest annual rainfall recorded was 154 inches in Monumental (1909), but Bagdad in the Mojave Desert once had no measurable rain for 25 months, a U.S. record.[33] Actual rainfall is highly variable and deviates significantly from the average more often than not. In 1996, for example, San Francisco had a 50 percent increase over "normal", while in the same year, Imperial County had less than 30 percent of its usual rainfall of 2.75 inches[34]. The winter of 1997-98 was one of the wettest on record, bringing devastating floods and mudslides. In 1997, Los Angeles experienced its longest dry spell in its history—219 days—followed by the wettest February (1998) in more than 100 years—more than 13.5 inches. The 1998 calendar year brought 27.85 inches to L.A.; the next year saw only 8 inches.[35]

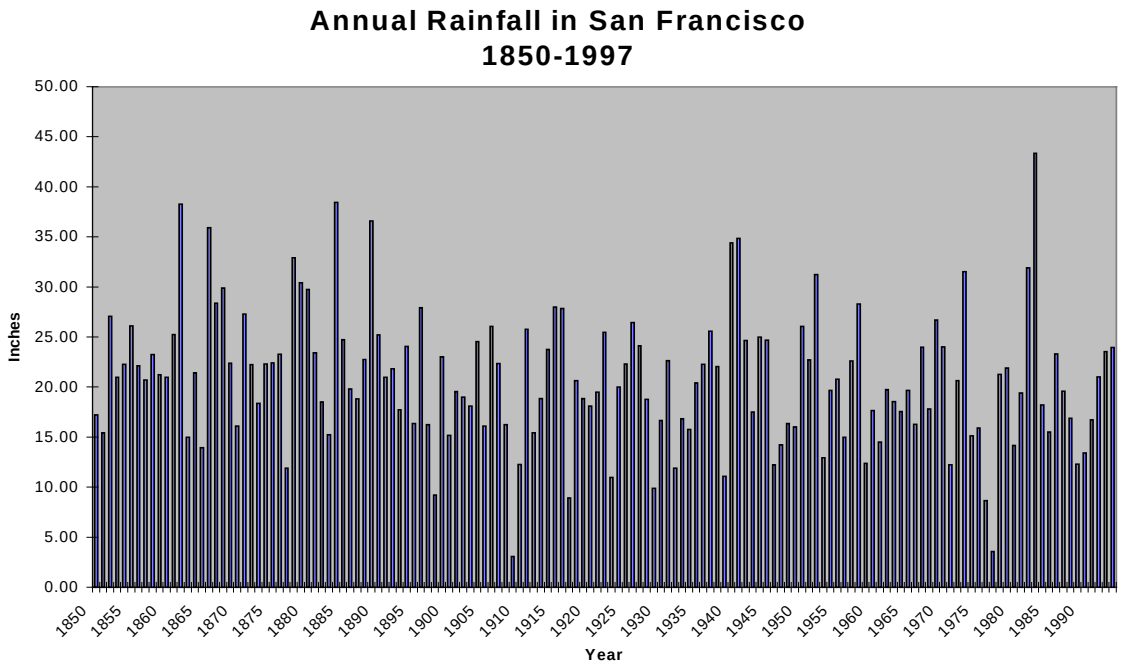
The map below indicates the spatial variability of precipitation in California. The graphs on the following page indicate variability over time.

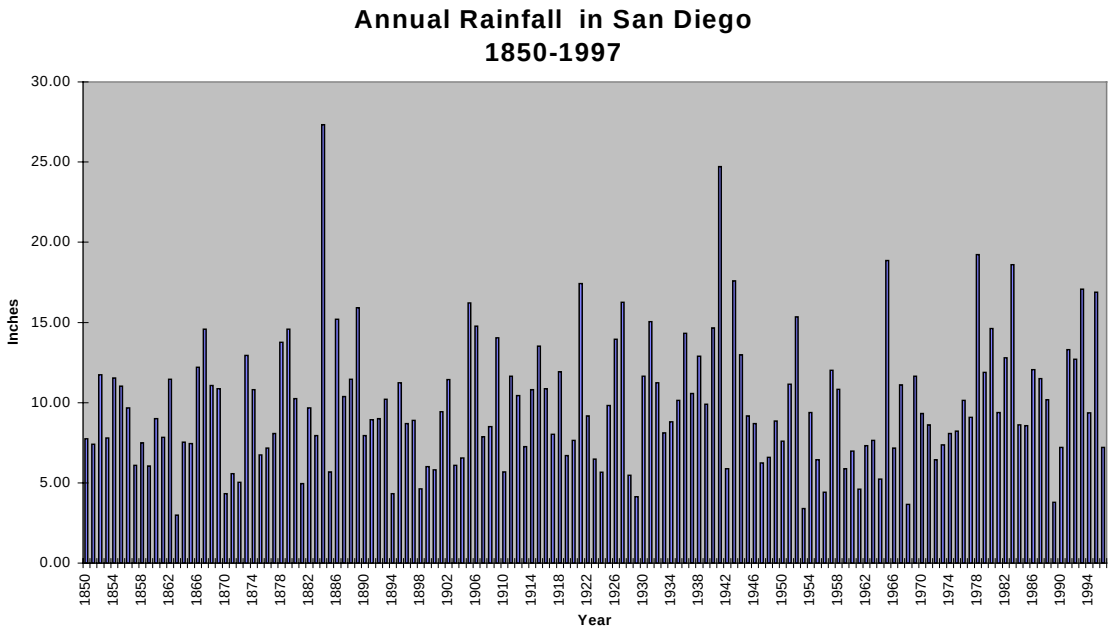
Distribution of Average Annual Precipitation
1961-1990



Source: Oregon State University[36]

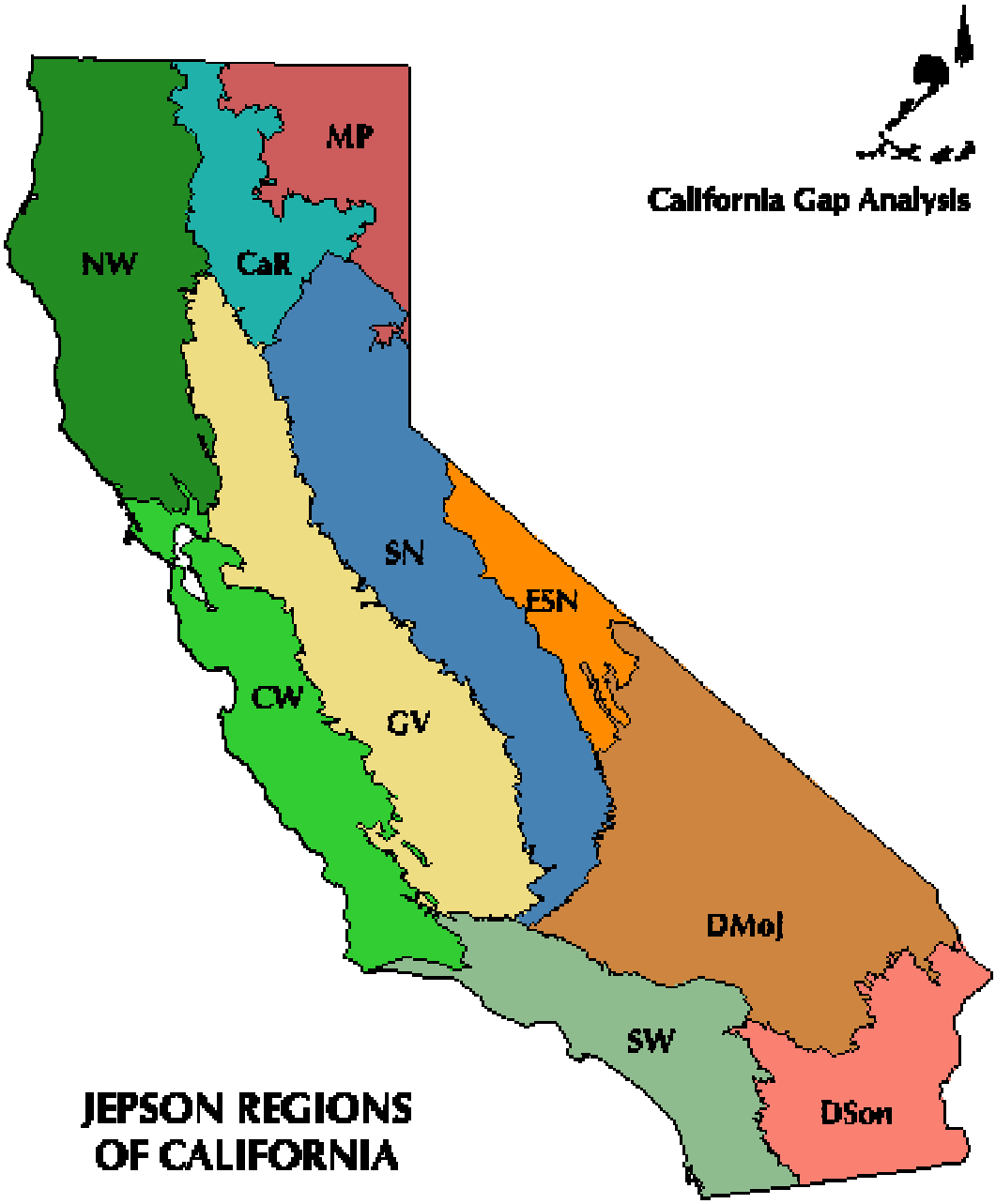
The following graphs of annual rainfall from 1850 to the late 1990s provide a sense of the annual variability in precipitation in San Francisco and San Diego.





California's geography is key to both its climate and the diversity of its ecosystems. The Sierra Nevada Mountains capture the moisture of Pacific storms, resulting in large amounts of

precipitation as snowfall in the mountains. Donner Summit has an 80-year average March snowpack of over 90 inches, and it reached nearly 320 inches in 1951-52. Owens Valley, lying in the Sierra rainshadow, is a true desert, receiving less than 6 inches of rain annually.[37] In wet years, the tremendous Sierra snowpack serves as a water storage system for much of the state, gradually releasing supplies during dry summers.



Source: California GAP Analysis, UCSB.[38]

California's Climate Zones

The Jepson Manual of California Flora has adapted Sunset Publishing Corporation's 24 horticultural zones of the west. These zones are geographically as well as climatically influenced.

Zones 1–3: Snowy parts of the West. Includes much of the Klamath, Cascade, Sierra Nevada, Inyo, Transverse, and Peninsular mountain ranges, where snow accumulates in winter.

Zones 7–9: Great Valley and Surrounding Low Mountains. Includes Sacramento and San Joaquin Valleys, foothills of the Klamath and Sierra Nevada mountains, and South Coast Ranges. Summers are very hot and dry, winters are moderately cold, with cold air collecting in the lowest areas of the valleys.

Zones 10–13: Deserts. Includes low deserts in the southeast, and the high deserts of the Mojave and eastern Great Basin deserts. Temperatures vary dramatically in the high deserts, with typically very hot summers, cold winters, and late spring frosts likely. In the low deserts, winter temperatures rarely drop below freezing, and summer temperatures reach well into the 100s.

Zone 14: Ocean-influenced Northern and Central California. Inland areas with ocean or cold air influence. Includes narrow bands inland from coastal ranges as well as low lands inland from the San Francisco Bay (Sacramento and Stockton).

Zones 15–17: Coastal Climates of Northern and Central California. Cool, moist coastal strip from Point Conception northward. Includes the foggy redwood forests, San Francisco Bay, and the Highway 1 corridor south of San Francisco.

Zones 18–19: Interior Valleys of Southwestern California. Valleys and slopes of the Transverse and Peninsular Ranges, including the San Bernardino area, that typically have hot, dry summers, with many areas experiencing winter frosts.

Zones 20–21: Ocean-influenced Southwestern California. Pockets of interior regions that receive both marine and continental influences. Includes vicinities of Ojai, Burbank, El Monte, and Ramona.

Zone 22–24: Coastal Climates of Southwestern California. The coast from Point Conception to San Diego, including coastal plains, the Los Angeles basin, and portions of the Transverse and Peninsular Ranges. Dominated by marine influences, but occasionally interrupted by the hot, dry Santa Ana winds that reverse the marine flow.

Source: *The Jepson Manual.* University of California Press, 1993.

California's Air Quality

The California Environmental Protection Agency notes that:[39]

> Air pollution is one of the major environmental challenges for California. Because of its potential for impacting human health, air pollution consistently ranks high among public concerns. Over 90 percent of Californians breathe unhealthy levels

> of one or more air pollutants during some part of the year. While air pollution can be a problem in nearly all regions of the state, the air quality of California's major urban areas is of particular concern. For example, the Los Angeles area is one of the regions with the worst air pollution problems in the entire country.

California's population, postwar industrial boom, agricultural success, and dependence on the automobile have resulted in troubling problems with air and water pollution. Cars and trucks are California's primary sources for air pollution, emitting ozone, carbon dioxide, carbon monoxide, nitrogen oxides, particulate matter, and other harmful substances.

California has had tremendous success in cleaning its air over the past two decades. Auto emission standards are the toughest in the nation. Per capita gasoline use is the ninth lowest in the country.[40] California's 1994 per capita carbon dioxide emissions were nearly 40 percent lower than the U.S. average.[41]

In the Los Angeles area, population density, cars, climate, and geography once conspired to create the nation's worst air quality. Other California cities such as Bakersfield and Fresno in the San Joaquin Valley face serious air pollution problems. Pollutants from the valley have also caused Sequoia National Park to have the worst smog of any national park—and more days of unhealthy ozone than Los Angeles and New York City combined.[42]

In the South Coast Air Basin (including Los Angeles, Orange, and parts of Riverside and San Bernardino Counties), federal 1-hour ozone standards were exceeded on 60 days in 1998; nevertheless, this is a dramatic improvement over the 167 days of violation in 1980.[43]

Ozone is largely a product of the transportation sector. Ozone (O_3) in the lower atmosphere (as opposed to stratospheric ozone) is produced when sunlight initiates a photochemical reaction between oxides of nitrogen (NO_x) and hydrocarbons, both products of fossil fuel combustion. Exposure to ozone for several hours can create respiratory distress in as many as 20 percent of healthy adults and children, while prolonged chronic exposure can cause irreparable lung damage.[44] Ozone also causes tissue damage to plants, decreasing productivity in agricultural crops, landscaping, and natural vegetation.

California's stringent auto emission control regulations and reformulated gasolines have made today's automobiles and trucks as much as 95 percent cleaner than cars running 30 years ago.[45] However, we have some 26 million vehicles on California roads, all emitting some pollutants. The increasing popularity of trucks and sport utility vehicles is also contributing to the state's problems—these vehicles produce 1.5 to 2.5 times the emissions of passenger cars. Increasing public pressure is now prompting automakers to commit to reduce emissions by producing more electric hybrid cars and fuel-cell vehicles, as well as improving fuel efficiency in trucks and sport-utility vehicles.

Another significant air pollutant is particulate matter less than 10 microns in diameter, known as PM10. Health problems can result from prolonged exposure to PM10, particularly the particles less than 2.5 microns which can easily penetrate deep into the lungs. Ash, soot, and dust are the

primary constituents of particulate matter pollution, but any solid or liquid particle smaller than 10 microns can contribute to this type of pollution. A major source of particulate matter is incomplete combustion of organic substances—from gasoline to wood. Various industrial activities—processing metal, wood, fiber, and many other materials—can also produce aerosols. In farming regions, agriculture contributes to particulate matter. Heavy equipment disking the soil and aerial application of pesticides and fertilizers can send huge amounts of dust and droplets into the air. An additional health concern from agricultural dust is the potential for soil pathogens to become airborne, such as that which causes Valley Fever.[46]

The potential implications of climate change and variability on health, and their relationship to air quality issues, is discussed in the section on health impacts.

Ecosystems Under Stress

Throughout California, wetlands, forests, rivers, woodlands, and other natural habitats have been and continue to be altered, diminishing the state's valuable natural diversity. Estimates of losses include the following: over 90 percent of California's wetlands have disappeared; sixty percent of the Sacramento-San Joaquin Delta's waters are diverted for human use; almost nothing remains of the Central Valley's native grasslands which once blanketed more than 20 million acres; native oaks are in serious decline; and nearly 90 percent of the state's riparian areas have been destroyed or seriously degraded.[47] In this increasingly stressed California region, the abundance of species unique to the state has led to an growing number of threatened and endangered species. Some species have already become extinct. The state and federal threatened and endangered species lists include 144 species and subspecies of mammals, birds, fish, reptiles, amphibians, and insects, [48] and 155 plant species.[49] The state's official mammal, the Grizzly Bear, has not been seen in California since the 1920s. The state reptile, the Desert Tortoise, is endangered, as is a subspecies of the state fish, the Golden Trout. The Coast Redwood, the state's official tree and the tallest living thing on Earth,[50] has been reduced to about 15 percent of its original range.[51] Some salmon runs are already extinct, and others have declined by more than 98 percent.[52] Nine California populations of salmon and steelhead are listed as threatened or endangered.[53]

California's Economy

California as a "G-7" Country

California's Gross State Product in 2000 was about $1.35 trillion.[54] Ranked as a nation, California would have the fifth largest economy in the world and would qualify for membership in the "G-7"—the group of seven largest national economies.[55]

Gross Product Ranking
G-7 Countries and California
2000

	billions of U. S. dollars[56]
United States	$9,896
Japan	$4,750
Germany	$1,873
United Kingdom	$1,415
CALIFORNIA	**$1,358**
France	$1,294
Italy	$1,074
Canada	$689

Sources: Compilation by author based on: California figure; California Technology, Trade, and Commerce Agency. *California: An Economic Profile*. January 2002. OECD countries from Organization of Economic Cooperation and Development. OECD Statistics, GDP, January 2002[57]

This level of economic activity is more than a curiosity to add to the state's list of superlatives. Climate change could have significant repercussions for California's economy. Public and private sector stakeholders have a stake in its well-being. The assessment of potential climate impacts on an economy of this magnitude resembles the national assessment efforts of other major countries.

California's Major Economic Sectors

California has a broad and diverse economy with strengths in many areas. The state produces 13 percent of the nation's goods and services,[58] and it is a prominent international competitor in manufacturing, agriculture, electronics, finance, entertainment, and other sectors. In 2000, venture capitalists invested $31 billion in California, nearly double that of the previous year. Silicon Valley alone attracted $25.8 billion in venture capital, 37% of that coming into the U.S.[59]

During the recession in the early 1990s, California's unemployment rate was 9.3 percent.[60] By the end of the decade, recovery brought December 2000's average rate to 4.6 percent, the lowest rate in more than 30 years. In 2000, more than 448,000 jobs were created in the state.[61] California's economy grew at an average annual pace of 8.9 percent between 1997 and 2000, outpacing a nationwide boom that saw an annual rate of 6.2 percent.[62] The economic expansion was felt throughout California and in nearly every major industry. Foreign trade, high technology, tourism, entertainment, and professional services led the state. The effects reached manufacturing, agriculture, construction, and housing markets. Personal income grew 7.9 percent in 2000.[63]

Top Economic Sectors[64]

Sector	*Revenue*	*Employees*
Tourism	$75 billion	1,109,000
Entertainment	$40 billion	262,000
Aerospace	$28 billion	170,900
Agriculture	$27 billion	418,000
Biotechnology	$20 billion	212,700
Apparel	$13 billion	144,000

Industry Highlights

California produces nearly every major commodity: lumber and paper, textiles and clothing, automobiles, natural gas, oil, gasoline, and other petroleum products, hardware, furniture, food and beverages, computers, software, industrial machinery, aircraft, and many other products. California employs nearly 2 million people in manufacturing durable and non-durable goods. An additional 831,000 workers are employed in wholesale trade, moving those goods from producers to retailers.[65]

Top Employment Sectors, 2000

Sector	*Employees*
Services	4,267,000
Retail Trade	2,470,000
Government	2,321,000
Manufacturing	1,944,000
Wholesale Trade	831,000
Finance, Insurance, Real Estate	823,000
Transportation	746,000
Construction	734,000
Agriculture	408,000
Total	**14,518,000**

Source: California Technology, Trade, and Commerce Agency. "California: An Economic Profile." January 2001.

California also leads the nation in exports. In 2000, California businesses exported more than $130 billion in products, representing 16 percent of all U.S. exports. Mexico displaced Japan as the state's top foreign customer, receiving more than $19 billion in California goods in 2000, compared to Japan's $17 billion. Electronic components, telecommunication equipment, and

electrical products made up 29 percent ($37.8 billion) of all exports, closely followed by industrial machinery, including computers and peripherals, at 29 percent ($37.6 billion). California produced $8.4 billion in processed and unprocessed food for export.[66]

Aerospace remains a strong factor in the state's economy. California accounts for about 20 percent of the U.S. aerospace industry, employing 170,900 workers and producing $28 billion in products. California is home to about 710 manufacturers of aircraft and parts, 270 makers of search and navigation equipment, and 96 producers of spacecraft and parts.[67] California received $19.3 billion in Department of Defense and NASA contracts in 1999.[68] A mainstay of southern California's economy, the aerospace industry suffered a decline as a result of defense-spending cuts in the post-Cold War era. In the 1990s, an estimated 15,000 jobs were lost in the Burbank area alone.[69] The growth of satellite telecommunications and navigation technology has added to this industry's core enterprise of producing air- and spacecraft.

At the end of the 1990s California had more than 900 **Internet**-related companies employing 382,000 people. The Internet industry is composed of numerous high technology manufacturing industries and services, including computer manufacture, circuit board manufacture, telecommunications, software publication, computer programming services, online information services, internet service providers, e-commerce businesses, and much more. California is home to some of the most successful internet technology companies in the world, including Intel, Apple, Hewlett-Packard, Packard Bell, Adobe Systems, Atari, Cisco Systems, National Semiconductor, Oracle, Sun Microsystems, 3Com, Symantec, and Yahoo! Since the mid-1990s, the Internet has been a driving force in the U.S. economy, fueling phenomenal growth in information technology sectors. These sectors increased their share of the U.S. output from 6.4 percent in 1993 to 8.2 percent in 1998, and accounted for more than a quarter of all economic growth since 1993.[70] In 2000 and 2001, however, tech–related industries have demonstrated their vulnerability.[71]

Environmental technology and **biotechnology** are terms used to define a broad spectrum of technologies that are primarily involved with air and water quality improvement and maintenance, waste and toxic materials management, development of alternative energy sources, development and production of pharmaceuticals and other health care products, biological engineering, environmental monitoring, and a broad range of research. California is a leader in environmental technologies. The industry is broken into three major components: service-oriented businesses, product-oriented business, and environmental industry infrastructure, including water and waste treatment systems and facilities, interior environmental controls, a variety of measurement and control devices, and engineering and other services. *Environmental Business International, Inc.* estimated that the environmental technology industry in California employed 200,000 people and generated $22 billion in revenues in the mid-1990s.[72]

Biotechnology combines engineering concepts with biological processes to produce substances and methods to create products used extensively in health care, as well as in agriculture and food processing. Its products and services encompass genetic engineering, pharmaceuticals and diagnostic systems and substances, as well as sophisticated research and testing laboratories. California is the world's leader in biotechnology and has one-third of the nation's biotech companies, including Genentech, Amgen, and Cetus Corporation, and generated 58 percent of

the nation's biotech revenues.[73] Many aspects of environmental technologies have strong links with California's university systems.

California has produced the highest **agricultural** crop value in the U.S. for more than 50 consecutive years. Of nearly 28 million acres in some from of agriculture in California, about 8.5 million acres are in harvested crops.[74] It is the leading dairy state, the number two cotton producer, and it grows more than half the nation's fruits, nuts, and vegetables. Total agricultural income exceeded $26 billion in 1997, nearly twice that of the second-ranked state, Texas. Exports amounted to nearly $6.7 billion in revenue.[75] California is the only state to produce commercial quantities of a number of important crops including almonds, artichokes, clingstone peaches, figs, raisins, walnuts, pistachios, nectarines, olives, dates, and prunes. Not only does the state lead the nation in growing crops and livestock, it is the largest employer in food processing—baking, canning, distilling, freezing, grinding, milling, and squeezing.[76] Wine is California's highest value-added agricultural product. California leads the nation in the production of all grape varieties, with the 2000 value of production at $2.80 billion.[77] California wine shipments accounted for approximately 70 percent of the U.S. wine market, with an estimated retail value well over $13 billion. Wine exports were valued at more than $500 million in 1999.[78]

California is the nation's fourth largest producer of **petroleum**, and ranks third in proven petroleum reserves.[79] Extracting and refining petroleum products produced gross revenue of $8.5 billion in 1994,[80] engaging over 110,000 workers.[81]

The general category of **services** is the largest sector of California's economy, employing more than 4.6 million workers—nearly one third of the state's workforce.[82] The sector includes activities ranging from business services such as advertising, credit reporting, computer programming, data processing, to health care, to neighborhood businesses such as dry cleaning.

California's variety of cultural and scenic attractions make the state one of the most popular destinations in the world, and **tourism** is one of its most vital economic sectors. From Disneyland to Yosemite, it is estimated that 45 million out-of-state and foreign travelers came to see the sights in 2000. California's travel and tourism industry generated an estimated $75.4 billion in 2000.[83] California's 11 million acres of state and national parks, recreational areas, and wilderness draw more than 35 million tourists to national parks annually, and another 76 million visit state parks.[84] Approximately 1.1 million people are employed in this state in jobs related to travel.[85] Nearly every county, town, and city reach out to tourists in one way or another, making tourism an important part of local economies. California has the nation's second highest income from fishing- and hunting-related activities—more than $5 billion in 1996.[86] The Division of Tourism estimates that each county receives on average $961 million in direct travel expenditures annually, ranging from $27.4 million in Modoc County to $12.5 billion in Los Angeles.[87]

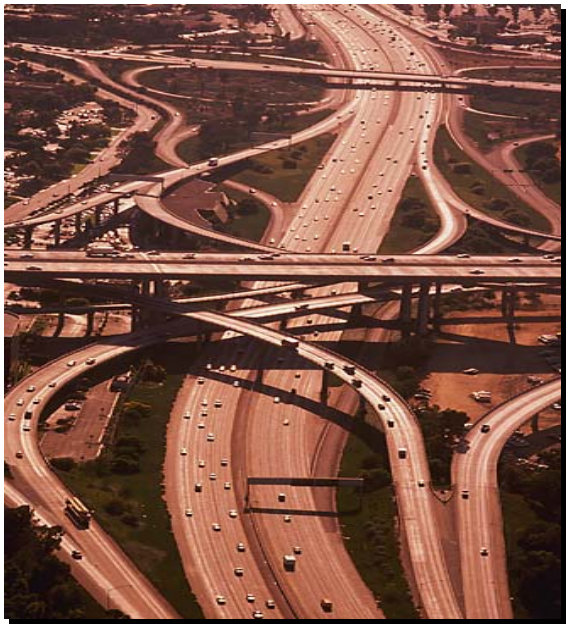
Entertainment has become one of the state's hallmark industries, with ties to computers and electronics as well as finance, tourism, and many other sectors. The motion pictures industry directly employed 190,300 people in 2000, with as many as 95,000 additional jobs in industries providing supplies and services to film production.[88] Some estimate that entertainment is a $40

billion annual business.[89] Entertainment helped rescue southern California from the economic slump resulting from the aerospace cutbacks. It is estimated that for every aerospace job lost, two were created in the entertainment industry.[90]

Supporting the state's economy are **financial industries** such as banking, insurance, and real estate. Depository institutions including commercial banks, savings and loans institutions, and credit unions, had total assets of over $417 billion in 1996.[91] The 1998 total gross product of finance, insurance, and related services was nearly $75 billion.[92] Real estate revenue exceeded $175 billion in 1998, a 422 percent increase in less than 20 years.[93] The median price of an existing single-family detached home in California during April 2001 was $262,420, a 10.7 percent increase over the $237,060 median one year previously. Median prices vary dramatically throughout the state, from a high of $1,595,000, in the Belvedere/Tiburon area to $115,530 in the High Desert.[94]

California's Infrastructure

California's economy and lifestyle are supported by one of the world's most extensive infrastructure systems. From water and transportation to energy and communications, the state relies on a complex system of pipes, cables, wires, canals, transmitters, roads, and other investments worth hundreds of billions of dollars. During occasional disruptions to these systems, Californians are reminded of these vital services they often take for granted. Events during the 1998 El Niño-related storms, for example, shut down major rail lines and interstate highways, severed communication and power lines, ruptured gas and oil pipelines, overwhelmed sewage systems, and damaged water supply systems.



California business leaders and senior state government officials have recently articulated a new focus on *natural systems* as infrastructure. As reflected in a statement released by the *California Environmental Dialogue*, there is growing support for investment in resource systems that are in fact a part of the state's infrastructure.[95]

> *We need increased investment* in our land, air, and water, and the life they support, to sustain a strong agricultural economy, growing tourism and recreational industries, healthy communities, and a quality of life that attracts the work force that underpins a vibrant economy.
>
> A vision for the twenty first-century must recognize that *California's habitats and natural communities are an integral part of the economic foundation* upon which future prosperity depends.
>
> California's rich and diverse ecosystems have provided us with an exceedingly generous bounty. *There are limits to these systems*, and it is time to return their generosity.

Water Systems

Water is critically important to both the state's economy and the ecosystems which ultimately underpin both economic productivity and the quality of life. Water's scarcity or abundance—in place and time—have historically created both physical impacts and human conflicts between north and south, cities and farms, environmentalists and developers, sportsmen and hydrologic engineers. The squabbling has gone on since before statehood, and current headlines indicate that the issues have not receded. An elaborate system of reservoirs, canals, aqueducts, and other engineered facilities is matched only by the even more elaborate set of laws and policies that govern the state's most contentious resource.

Thirst for water in California spawned an unprecedented control of nature. The water diversion, conveyance, and storage systems developed in California in the 20th century, such as the Central Valley and State Water Projects and the Colorado and Los Angeles Aqueducts, are remarkable engineering accomplishments. These water works move millions of acre-feet of water around the state annually. The state's 1,200-plus reservoirs have a total storage capacity of more than 42.7 million acre feet (maf).[96] The state's water systems have made the Central Valley one of the nation's most productive agricultural regions. The valley is virtually a desert; Bakersfield receives about six inches a year and Fresno less than 12, while the annual average evaporation potential in the Valley exceeds 60 inches.[97] More than seven million acres are irrigated in the Central Valley, representing more than 75 percent of the state's total irrigated acreage.[98]

California Average Annual Water Supply and Extractions

Water Source	Million Acre Feet per Year (mafy)
Precipitation	193.0
Natural recharge, percolation, and non-developed uses (a)	122.0
Surface runoff (historical range: 15 mafy [1977] to 135 mafy [1983])	70.8
Average annual water supply (b)	85.0
Total groundwater resources	850.0
Economically recoverable groundwater resources	250.0
Extractions of surface water (c)	21.6
Extractions of groundwater	
"Use" of groundwater (does *not* include overdraft)	7.1
Overdraft (d)	1.3
"Net" use of groundwater ("use" plus overdraft)	8.4
Surface storage capacity (reservoirs) (e)	42.8
Delta extractions (f)	10.3
Reclaimed water	0.2
Desalination	0.017
Imported Water	
Colorado River imports (g)	5.2
"Local imports"	1.0

(a): "Non-developed" uses are evaporation, evapotranspiration from native plants, and percolation
(b): Appears to include groundwater extractions including overdraft of 15 mafy and surface at 70 mafy.
(c): Based on sum of local, SWP, CVP, and other federal projects.
(d): DWR projects no overdraft from 2000 forward (Vol. 1, p. 6, Table 1-2), although it states on the same page that "...the reductions in overdraft seen in the last decade in the San Joaquin Valley will *reverse as more ground water is pumped* to make up for reductions in surface supplies from the Delta."
(e): California Department of Water Resources, Division of Dams. "Dams Statistical File," July 1997.
(f): Based on figures for SWP and CVP.
(g): California's "normal tear apportionment" is 4.4 mafy

Sources: California Department of Water Resources. *California Water Plan Update*, Bulletin 160-93. 1994. California Legislative Analyst's Office. Colorado River Water: Challenges for California." October 16, 1997. (http://www.lao.ca.gov/101697_colorado_river.html)

With very real limits to the state's water system, and every major supply source being reduced, the state's water systems may be fairly said to be stressed. Every major water supply source in California is currently beyond the physical or legal capacity to be sustained.

Three principle sources provide the state with water: surface water, which is often diverted or extracted and stored in reservoirs; groundwater; and imported supplies, principally from the

Colorado River. (Conjunctive use of surface and groundwater, re-use of agricultural and urban water, inflow from Oregon, and other factors make precise accounting for water supplies a complicated task.)

On average, about 193 million acre feet per year (mafy) falls as precipitation, two-thirds of which falls in the northern one-third of the state.[99] About 71 mafy is surface runoff, stored and redistributed for human use.[100] The Colorado provides more than 60 percent of the 8.4 million acre-feet used in southern California.[101] Groundwater supplies an average of about 7 mafy, but in drought years, this figure may increase drastically. Groundwater overdraft (extractions exceeding recharge over time) and contamination has reduced the availability of groundwater supplies throughout the state, and salt water intrusion in coastal aquifers is already a problem in some areas.[102]

Water is extracted from natural systems and used in California primarily for urban and agricultural purposes. The urban water use sector includes residential, commercial, industrial, and institutional uses, as well as municipal uses such landscaping and fire fighting. As the state's population continues to grow, urban uses of water are steadily increasing. Total agricultural use, however, peaked at the end of the 1980s and is declining.[103] In the early 1970s, agriculture used about 85 percent of the state's developed water supply.[104] By the end of the 1980s, the percentage of the state's water used by agriculture had fallen to 80 percent.

Irrigated land area increased from about 4 million acres in 1930 to a high in 1981 of 9.7 million acres.[105] In place of the continuing increase in water used for irrigation projected in earlier forecasts, the state now projects a continued decline in water use for agriculture.[106] Land retirement, crop shifting, water transfers, and improved efficiencies in irrigation as well as conveyance and management will all contribute to a reduction in water used for irrigation.[107] Despite this decline, however, total extractions from the state's water systems has increased through the years, with flows for the environment decreasing as a result.

California's normal year allocation of Colorado River water is 4.4 mafy, but the state has been taking 5.2 mafy through the use of "surplus" water.[108] The state has agreed to reduce its extractions back to the 4.4 mafy figure in the next decade and a half.

An average of 1.3 mafy of groundwater extractions is overdraft.[109] In severe drought years, this overdraft may be as high as four to 10 mafy,[110] which drastically depletes economically recoverable groundwater resources.

At the outset of the 1990s, Henry Vaux concluded his analysis of California's water situation in *Global Climate Change and California: Potential Impacts and Responses*, with the statement: "Today California's water economy is not in good shape. Even in average years, water supplies are balanced with water use only because of groundwater mining, a practice that cannot be sustained indefinitely."[111]

As a consequence of past management practices, the state is now working to restore some of the devastation of aquatic, riparian, and wetland ecosystems. The stresses already in place are causing the list of threatened and endangered species to continue to grow. As much as 90

percent of the state's riparian habitat has been lost, 95 percent of the state's wetlands have been destroyed,[112] and 95 percent of the salmon and steelhead habitat for spawning in the state's Central Valley have been lost.[113]

Pressures on water supplies flowing through the Sacramento–San Joaquin Delta are the subject of a major water-use controversy. The largest remaining wetland in the western U.S., the Bay-Delta provides habitat for more than 120 species of fish and other wildlife.[114] For years, urban and agricultural interests have over-appropriated the state's water. Legal mandates to restore damaged ecosystems, such as the *Central Valley Project Improvement Act*, and requirements to comply with various laws including the *Endangered Species Act* (ESA), are driving an extensive evaluation of water management. A joint effort by state and federal agencies known as CALFED is currently seeking to develop a process to restore the damaged systems and specific species listed under the ESA, and to manage the Delta's water resources more sustainably to supply urban and agricultural users.[115]

Fundamental and historic change is occurring in California water management and policy. The values and logic that are emerging to guide water policy, along with physical and economic constraints, portend a new basis for water policy and management in the future. In response to environmental damage, both the courts and Congress have established requirements for *restoration* of ecosystems and species, and they have required mitigation of environmental damage. In particular, environmental values and policies that reflect society's growing demand for environmental preservation and restoration are increasingly driving policy. To achieve these policy goals, water rights have been altered and new priorities are being established.

For example, in order to restore environmental damage, court decisions and State Water Resource Control Board decisions on the Mono Basin limit diversion of Sierra water sources to Los Angeles.[116] In the past, Los Angeles has relied on this water for a share of its annual consumption.

Commenting on the "dramatic changes" occurring in water law to address these problems, Arthur Littleworth observed:[117]

> Venerable court decisions that *historically defined the rules* governing riparian, appropriative and overlying water rights are now less relevant to California water issues than the Federal Endangered Species Act, the Clean Water Act, the public trust doctrine, "fixing" the Delta, the thicket of state and local regulations affecting water transfers, and the newly developing programs to manage local supplies.

Environmental considerations, long neglected in water policy, are now a determining factor. Littleworth and Janice Weis comment further:[118]

> In the early 1990's, the listing and proposed listing of water-dependent species in the Bay-Delta *has essentially taken control* over the operation of the State Water Project and the Federal Central Valley Project.

The challenges posed by climate change and variability will add to the already difficult water problems facing the state. As Henry Vaux noted in the early 1990s: "It is not unreasonable to speculate that water-related losses in California due to global climate warming could amount to as much as a billion dollars annually."[119] Billions of dollars of facilities have been proposed to add to the state's prodigious plumbing system. Widely divergent perspectives exist regarding response strategies to climate change. Some view the prospect as a reason to build more dams. Others see a need for improvements in efficiency and greater use of market tools, including price signals that more closely reflect true costs. One certain prediction is that the debates will continue and intensify with climate-induced stresses layered onto a serious existing problem.

Transportation Systems

Californians have long been defined by their mobility, made possible largely by the automobile – and petroleum. There are more than 21 million licensed drivers in the state,[120] and more than 27.7 million cars, trucks, trailers, and motorcycles,[121] traveling over an intricate maze of 167,000 miles of streets, roads, and highways. Los Angeles County alone has nearly 21,000 miles of roads.[122] Nearly 17 billion gallons of motor vehicle and diesel fuel were distributed in California in 1999.[123]

The transportation sector consumes 46 percent of California's energy[124] and produces by far the largest amount of CO_2 emissions.[125] Fewer than 20,000 of the 26.5 million vehicles in California are fueled by "alternative" energy sources, mostly ethanol-gasoline blends or natural gas. This dependence on gasoline-powered transportation in the state has resulted in some of the nation's worst air quality.

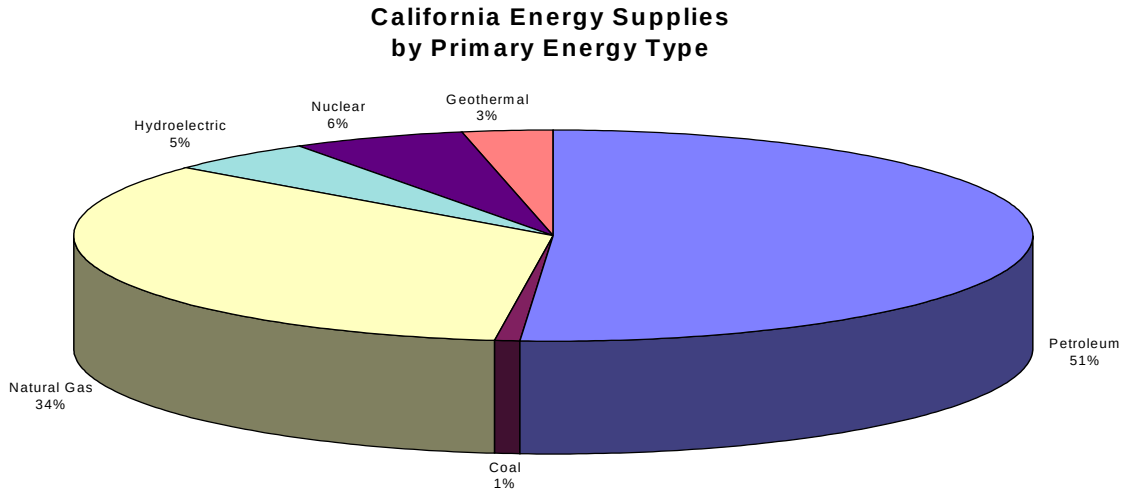
Transport of goods is a critical element of California's foreign and domestic trade. The state's important position in the world's economy makes it a major center for handling foreign trade. The Los Angeles/Long Beach harbor complex is the busiest container port in the nation.[126] In 2000, shipments by land, sea, and air through California ports totaled $392 billion – an increase of nearly $100 billion over 1996. Of the $148.6 billion in exports, 90 percent was California-produced goods. Nearly 39 percent was destined for Japan, the Republic of Korea, and Mexico.

In the 1990s, California experienced weather-related impacts to transportation systems including flooded airports, interstate highways and roads washed out, land-slides disrupting major rail lines, and heat waves causing an 8-land freeway to buckle. Future impacts due to extreme events and other impacts of climate change could pose important challenges.

Energy Systems

Energy systems are both the principle cause of climate change and a sector vulnerable to the impacts of change. While the focus of this assessment is on the latter, basic information on California's energy system structure and greenhouse gas emissions is included. This information is provided both to develop a baseline for consideration of physical impacts and because future policy responses to climate change will in themselves constitute important impacts for the state. Given the state's experience and leadership in many aspects of energy systems – from renewable energy technologies, advanced transportation systems, and other technologies implemented in the state – it is important to assess the potential impacts at both the energy systems and the policy world. It is also probable that key sectors of California business could benefit from increased demand for certain products and services as part of future climate change response strategies.

California is the tenth largest consumer of energy in the world[127] with a total consumption of more than seven quads (quadrillion BTUs).[128] The transportation sector consumes 46 percent of California's energy; 31 percent is used by industry; 13 percent is residential; and 10 percent is commercial.[129]



Source: California Energy Commission. (http://www.energy.ca.gov)

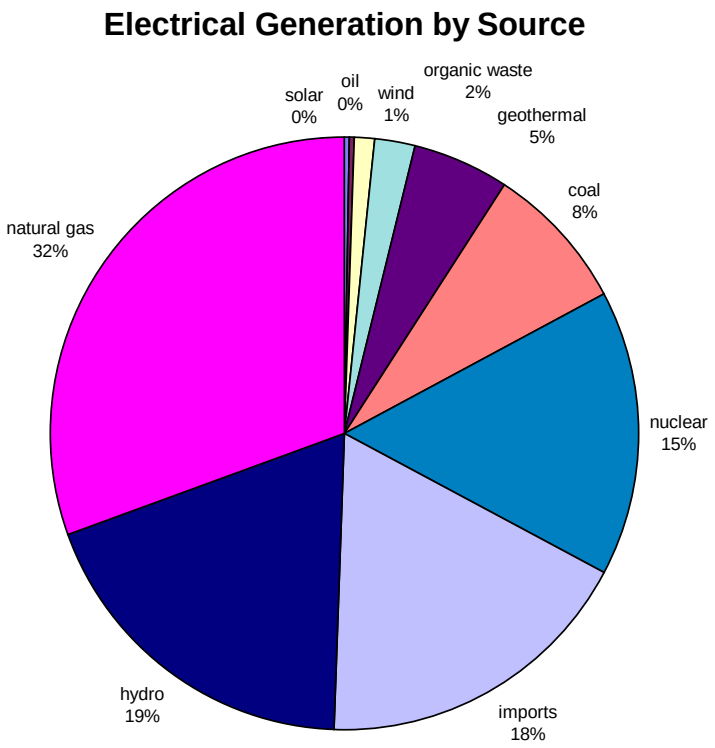
The state has the country's second-highest total energy consumption, trailing Texas. On a per capita consumption basis, however, California ranks 47th in the nation, and on the basis of energy used per dollar of gross product, California ranks 45th.[130] California has become significantly more efficient in energy use over the last two decades, decreasing per capita consumption by about 14 percent. California per capita primary energy consumption decreased from a level of more than 80 percent of the U.S. average in 1975 to 68 percent in 1997.[131] Californians used

about seven fewer barrels of oil equivalent in energy per person in 1995 than in 1975. Despite the improvements in energy efficiency, California's net use is increasing.

California is not energy self-sufficient. Half of the petroleum, 83 percent of the natural gas, and nearly 18 percent of the electricity used are imported from out-of-state. The state's need for imported power in growing: between 1989 and 1999, imports from the Pacific Northwest increased nearly 47 percent.[132]

California's electricity use increased an average of 2.1 percent per year since 1980. However, during the economic boom of the 1980s, the growth rate of electricity use was 3.2 percent; the rate through the 1990s was only 0.9 percent, reflecting the severe economic slowdown in the early 1990s.[133] The greatest share of electricity consumption is in the commercial sector, using 36 percent of the total and growing at an average annual rate of 3.3 percent. Residential electricity consumption has increased 2.3 percent per year on average, and industrial demand has grown at 1.4 percent per year.[134] By some projections, the state's population could increase 50 percent by 2020, and energy requirements will continue to rise with it.[135]

California has developed one of the world's most diverse electric generation systems in terms of primary energy sources used to produce electricity. More than 1,300 power plants generate electricity in California.[136] Natural gas, oil, nuclear, hydro, coal, geothermal, wind, solar, and biomass all contribute to the generation mix. Natural gas and electricity imports are used more during periods of drought, which reduces hydroelectric generation. Natural gas contributed heavily to California's electric generation over the last 10 years because of the growth in co-generation, the continued low price of gas, the drought, and the shift from use of oil to natural gas to reduce air pollution.



Source: California Department of Finance. California Statistical Abstract. Table J-11 "California Electrical Energy Generation." December 17, 1997. (http://www.dof.ca.gov/html/fs_data/stat-abs/toc.htm)

Though still a small fraction of the total generation mix, renewable energy sources – including hydro, geothermal, wind, biomass, and solar – have been developed and commercialized in California and show considerable promise for the future. California was the world leader in the development and installation of wind energy technology until recently. Advanced technologies for transportation and energy conversion, such as fuel cells and solar photovoltaic cells, are also important aspects of California's energy sector. Both for in-state use and for export, the potential for expansion of production and use of these technologies is potentially a major economic opportunity for the state.

California Institutions Addressing Climate Change

California's environmental programs principally fall under the responsibility of the California Resources Agency and California Environmental Protection Agency (Cal EPA).[137] The Resources Agency is responsible for the stewardship, conservation, management, and enhancement of California's natural resources, including fish, wildlife, and forests. There are 28 departments, commissions, and conservancies within the Agency.[138]

The California Resources Agency

Department of Boating and Waterways
Department of Conservation
Department of Fish and Game
Department of Forestry and Fire Protection
Department of Parks and Recreation
Department of Water Resources
California Conservation Corps
California Coastal Commission
California Energy Commission
California State Lands Commission
San Francisco Bay Conservation and Development Commission
Delta Protection Commission
Colorado River Board of California
State Reclamation Board
Board of Forestry
Fish and Game Commission
Mining and Geology Board
Native American Heritage Commission
Parks and Recreation Commission
State Historic Resources Commission
California Water Commission
Baldwin Hills Conservancy
California Tahoe Conservancy
Coachella Valley Mountains Conservancy
San Gabriel & Lower Los Angeles Rivers & Mountains Conservancy
San Joaquin River Conservancy
Santa Monica Mountains Conservancy
State Coastal Conservancy

Source: http://ceres.ca.gov

Cal EPA is responsible for environmental protection, water and air quality, and hazardous waste. There are six departments and boards within Cal EPA:[139]

California Environmental Protection Agency

Air Resources Board
California Integrated Waste Management Board
Department of Toxic Substance Control
Department Pesticide Regulation
State Water Resources Control Board
Office of Environmental Health Hazard Assessment

Source: California Environmental Protection Agency (http://www.calepa.ca.gov/)

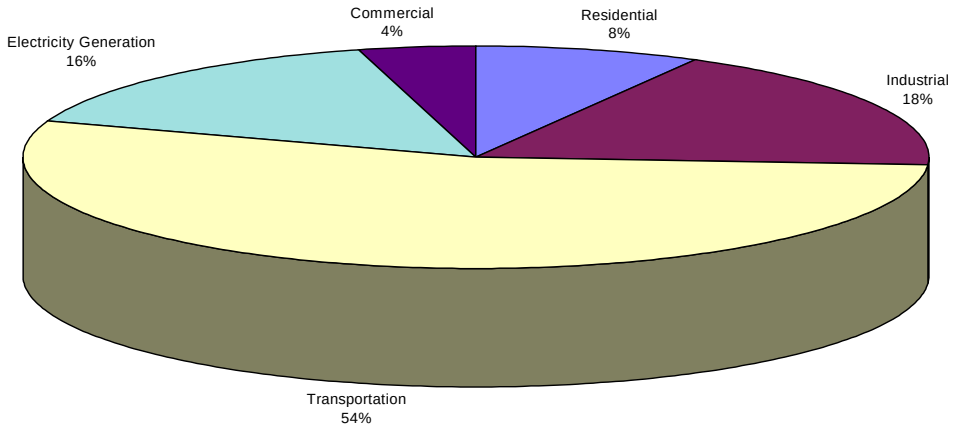
California Greenhouse Gas Emissions

Carbon dioxide, methane, and nitrous oxide are the three primary greenhouse gases produced by human activity. Carbon emissions are attributed to four major sources: transportation, industrial and commercial activities, electric utilities, and residential uses. The U.S. is by far the world's largest producer of greenhouse gases, both in terms of per capita and total emissions. The U.S.

released 1.56 billion tons of carbon dioxide into the atmosphere in 2000. Nationwide, CO_2 emissions are accelerating. The average annual growth rate is 1.5 percent, but in 2000, the rate jumped to 2.7 percent. Transportation-related emissions rose 2.6 percent, while industry emissions went up only 1.8 percent. The sudden increase has been attributed to a number of factors, including a cold winter in the Northeast that prompted higher demand for heating oil; a drought in the Pacific Northwest that decreased production of clean hydroelectric power; and the still growing popularity of fuel-inefficient sport utility vehicles and trucks.[140]

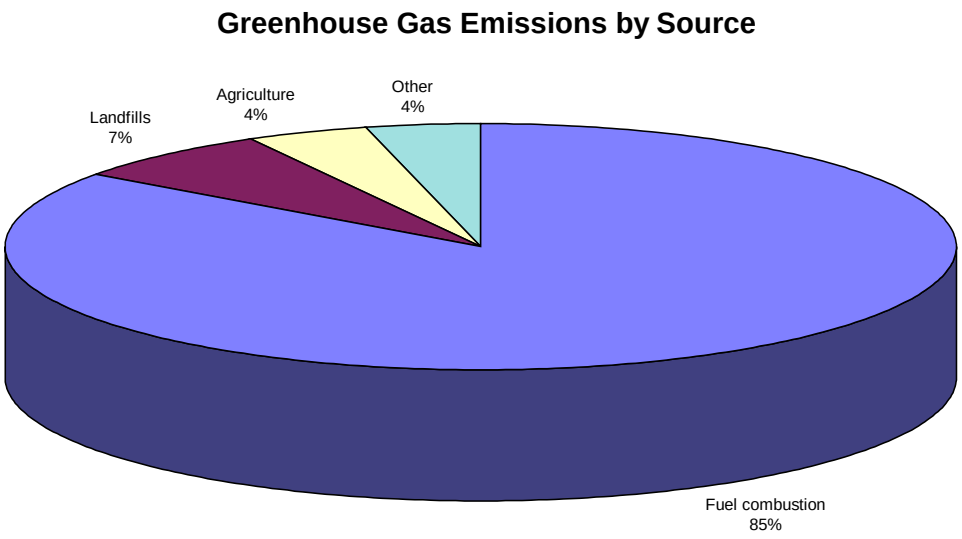
California's carbon dioxide emissions have been relatively stable since the mid-1980s, but have decreased slightly from a peak in the late 1970s, partly due to a switch from fuel oil to natural gas in power plants. Emissions per gross state product has dropped dramatically, demonstrating a substantial increase in energy efficiency in the economy, a decrease in the use of high carbon content fuels, and an overall shift in the economy away from energy-demanding manufacturing.[141] But as both the state's population and economy continue to grow, so will emissions. The California Energy Commission estimates that by 2010, total greenhouse gas emissions will increase about 15 percent, with fossil fuel combustion still producing about 85 percent of the total.[142]

Carbon Emissions by Sector



Source: California Energy Commission. "Historical and Forecasted Greenhouse Emissions Inventories for California." September 30, 1997.

Carbon dioxide emissions due to electricity generation are considerably greater for out-of-state sources than from electricity generated within California. In-state power sources produce nearly 170,000 gigawatt hours (GWhr), while emitting a little over 50 thousand tons of CO_2 (0.29 tons per GWhr). Out-of-state electrical generation plants provide California with about 100,000 GWhr, while producing 60 thousand tons of CO_2 (0.60 tons per GWhr), more than twice as much. This is due to the coal-based power that is imported into the state.



Source: California Energy Commission. "Historical and Forecasted Greenhouse Emissions Inventories for California." September 30, 1997.

Summary

California is, in a number of respects, on a par with major nation states. Its economy is highly productive and diversified. Its population is large, diverse, and growing rapidly. Its natural resource systems and ecosystems are unique and valuable assets. Its problems are also large.

Climate change and variability will potentially impact many, if not all, of these important elements. Some changes may be beneficial, others not.

The following sections of this report examine several important elements of the natural and human systems in California.

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[49] California Department of Fish and Game. "State and Federally Listed Endangered, Threatened, and Rare Plants of California." April 2001. (http://www.dfg.ca.gov/whdab/TEPlants.pdf)

[50] (Up to 350 feet.) Brockman, C. Frank. 1968. *Trees of North America*. Golden Press. p. 50.

[51] Palmer, Tim, Ed., 1993. *California's Threatened Environment*. Island Press. p. 8.

[52] Nelson, Barry. "Troubled Shores: The Ocean, Bays, and Estuaries." in California's Threatened Environment, Tim Palmer, ed. Planning and Conservation League Foundation, Island Press, 1993. p. 113.

[53] US Fish and Wildlife Service Threatened and Endangered Species System (TESS). "Listings by State and Territory, as of 5/13/2001." http://ecos.fws.gov/webpage/webpage_usa_lists.html#CA

[54] California Technology, Trade, and Commerce Agency. "California: An Economic Profile." January 2001.

[55] The "G-7" countries are the largest industrialized economies in the world — Canada, France, Germany, Italy, Japan, United Kingdom, and United States. They meet periodically to coordinate economic and foreign policy matters.

[56] At current (2001) prices and exchange rates. (as of 12/2001) http://www.oecd.org/std/gdp.htm

[57] OECD at (http://www.oecd.org/std/gdp.htm), California at http://commerce.ca.gov/state/ttca Note: China, Brazil, and Mexico are among the top 10 economies but they are not OECD countries. China's GDP in 2000 (including Hong Kong) was $1,243 billion, Brazil's was $588 billion, and Mexico's was $575 billion.

[58] California Technology, Trade, and Commerce Agency. "California. An Economic Profile." January 2001.

[59] California Technology, Trade, and Commerce Agency. "California. An Economic Profile." January 2001.

[60] California Department of Finance. California Statistical Abstract. Table C-1, Employment and Unemployment, California and Metropolitan Areas, 1971–1999. January 2001.

[61] California Technology, Trade and Commerce Agency. "California: An Economic Profile." January 2001.

[62] California Technology, Trade and Commerce Agency. "California: An Economic Profile." January 2001.

[63] California Technology, Trade and Commerce Agency. "California: An Economic Profile." January 2001.

[64] Figures from 1999 unless otherwise noted. Tourism figures from 2000; includes transportation, accommodations, food service, retail trade, and recreation. Entertainment figures from 2000; includes film, music, television, and related products and services. Agriculture employment is seasonally averaged. Sources: California Division of Tourism, Tourism Research (http://gocalif.ca.gov/research/tlkngpts.html); Agricultural Statistical Review; Bates, James. "In Local Economy, Hollywood is a Star." Los Angeles Times, January 18, 1998. California Trade and Commerce Agency.

[65] California Technology, Trade and Commerce Agency. "California: An Economic Profile." January 2001.

[66] California Technology, Trade, and Commerce Agency. "California. An Economic Profile." January 2001.

[67] California Technology, Trade, and Commerce Agency. "Industry Profiles: Aerospace." (http://commerce.ca.gov/ersi/oer/profiles/aerospace.html). May 5, 2001.

[68] California Department of Finance. California Statistical Abstract, Table P-43. January 2001.

[69] Leovy, Jill. "Show Business Fills the Aerospace Employment Gap in Burbank." Los Angeles Times, January 18, 1998.

[70] California Technology, Trade & Commerce .The Internet Economy. (http://commerce.ca.gov/ersi/oer/profiles/internet.html)

[71] For the first time in its history, Cisco Systems revealed a net quarterly loss in May 2001; in 2000, the Internet networking equipment giant briefly had the largest market capitalization of any company in the world. Cisco is among many technology companies that have announced layoffs in the first half of 2001.

[72] California Technology, Trade & Commerce, Office of Economic Research. "The California Environmental Technology Industry." (http://commerce.ca.gov/ersi/oer/profiles/envirote.html) Revenue data for 1994, employment for 1997.

[73] California Trade and Commerce Agency. "Industry Profiles: Biotechnology in California." May 2000.

[74] California Department of Finance. California Statistical Abstract. Table G-7, California Farms. January 2001.

[75] California Department of Food and Agriculture. (http://www.cdfa.ca.gov/statistics/california.html)

[76] California Technology, Trade, and Commerce Agency. "California. An Economic Profile." January 2001.

[77] California Department of Food and Agriculture. (http://www.cdfa.ca.gov/statistics/california.html)

[78] Wine Institute. "2000 California Wine Sales Up For Seventh Consecutive Year." (http://www.wineinstitute.org/communications/statistics/Sales_00.htm)

[79]California Energy Commission. "California Historical Energy Statistics." December 16, 1997. (http://www.energy.ca.gov/energy/reports/stats/statistics.html#electricity)

[80] California Department of Finance. California Statistical Abstract. Table D-2, "California Gross State Product." December 17, 1997. (http://www.dof.ca.gov/html/fs_data/stat-abs/toc.htm)

[81] Western States Petroleum Association, http://www.wspa.org/factcpio.htm, January 2002.

[82] California Technology, Trade, and Commerce Agency. "California. An Economic Profile." January 2001.

[83] California Division of Tourism, Tourism Research "Tourism & the Economy" (http://gocalif.ca.gov/research/tlkngpts.html)

[84] California Department of Finance. California Statistical Abstract. Table P-42, Visitors to State Parks and Recreation Areas, 1999.

[85] California Technology, Trade, and Commerce Agency. "California: An Economic Profile." January 2001.

[86] "Reel Dollars." Los Angeles Times, February 26, 1998.

[87] California Tourism Research. "California Tourism Talking Points." (http://gocalif.ca.gov/research/ tlkngpts.html) December 16, 1997.

[88] California Technology, Trade, and Commerce Agency. "California: An Economic Profile." January 2001.

[89] Bates, James. "In Local Economy, Hollywood is a Star." *Los Angeles Times*, January 18, 1998.

[90] Bates, James. "In Local Economy, Hollywood is a Star." *Los Angeles Times*, January 18, 1998.

[91] California Department of Finance. California Statistical Abstract. Table L-1, "Domestic Demand and Time Deposits, all Insured Commercial Banks Headquartered in California." January 2001.

[92] California Department of Finance. California Statistical Abstract. Table D-2, California Gross State Product, Selected Years." January 2001.

[93] California Department of Finance. California Statistical Abstract. Table D-2, California Gross State Product, Selected Years." January 2001.

[94] California Association of Realtors. "Median Home Price Rose 10.7 percent in April; Home Sales Increased 0.5 percent." May 25, 2001. (http://www.car.org/newsstand/news/may01-5.html)

[95] California Environmental Dialogue, 2001. *Habitat and Prosperity: Protecting California's Future*, http://www.cedlink.org/publications/CEDhabitat.pdf (Emphasis added.) The participants in the dialogue include: ARCO Products (now part of BP), Audubon Society, Bank of America, California Council for Environmental and Economic Balance, California EPA, Chevron Corporation, Earth Island Institute, Environmental Defense, General Motors, Hewlett-Packard Company, Lockheed Martin, Natural Resources Defense Council, Nature Conservancy, Pacific Gas & Electric Company, Planning and Conservation League, Resources Agency of California, Sierra Club, Southern California Edison, Sustainable Conservation, Trust for Public Land, Union of Concerned Scientists, U.S. Environmental Protection Agency, Walt Disney Company, and Waste Management.

[96] California Department of Finance. California Statistical Abstract. Tables G-2, "Gross Capacities of Reservoirs by Hydrographic Region," and G-3 "Major Dams and Reservoirs of California." January 2001. http://www.dof.ca.gov/html/fs_data/stat-abs/toc.htm

[97] Kahrl, William L., et al. 1979. *The California Water Atlas*. California Department of Water Resources. pp. 5, 13.

[98] California Department of Finance. California Statistical Abstract. Table G-5 "Net Irrigated Land Acreage." January 2001.

[99] Kahrl, William L., et al. 1979. *The California Water Atlas*. California Department of Water Resources. p. 3.

[100] California Department of Water Resources, 1994, *California Water Plan Update*, Bulletin 160-93.

[101] California Legislative Analyst's Office. "Colorado River Water: Challenges for California." December 16, 1997. (http://www.lao.ca.gov/101697_colorado_river.html)

[102] California Department of Water Resources, Bulletin 160-98, *The California Water Plan Update*, November, 1998.

[103] California Department of Water Resources, November 1987, California Water: Looking to the Future, Bulletin 160-87 p.9; California Department of Water Resources, 1994, California Water Plan Update, Bulletin 160-93.

[104] California Department of Water Resources, Bulletin 160-74, 1974, p.2.

[105] California Department of Water Resources, November 1987, California Water: Looking to the Future, Bulletin 160-87 p.9.

[106] California Department of Water Resources, 1994, California Water Plan Update, Bulletin 160-93, Vol. 1, pp. 159-184. Projection for 2020 on p.181, Table 7-13. (See Figure 7-1 on page 159 for a comparison of Bulletin 160 projections.)

[107] DWR includes extensive discussion of the changes in the agricultural sector and in its water use in Bulletin 160-93.

[108] California Legislative Analyst's Office. "Colorado River Water: Challenges for California." December 16, 1997. (http://www.lao.ca.gov/101697_colorado_river.html)

[109] California Department of Water Resources, 1994, California Water Plan Update, Bulletin 160-93.

[110] Kahrl, William L., et al. The California Water Atlas. California Department of Water Resources, 1979. p. 3.

[111] Vaux, Henry, "Global Climate Change and California's Water Resources", in Knox, Joseph B., ed. Global Climate Change and California: Potential Impacts and Responses. University of California Press, 1991. p.95.

[112] Emory, J. "Just Add Water," Nature Conservancy, Nov.-Dec. 1994. California's remaining wetlands, public and private, total approximately 300,000 acres, California State Lands Commission. California's Rivers: A Public Trust Report, 1993.

[113] California State Lands Commission. *California's Rivers: A Public Trust Report*, 1993.

[114] California Water Clearinghouse. "California's Bay-Delta Estuary: Restoring a National Treasure." Undated.

[115] CALFED. http://calfed.water.ca.gov/

[116] *National Audubon Society v. Superior Court of Alpine County*, 33 Cal. 3d 419, 189 Cal. Rptr. 346 (1983), cert. denied, 464 U.S. 977 (1983) and SWRCB D-1631.

[117] Littleworth, Arthur L., and Eric L. Garner. 1995. *California Water*, Solano Press, Point Arena, California, p. vi. (Emphasis added)

[118] Janice L. Weis, "Threatened and Endangered Species", in: Littleworth, Arthur L., and Eric L. Garner, 1995, *California Water*, Solano Press, Point Arena, California, p. 141. (emphasis added).

[119] Vaux, Henry, "Global Climate Change and California's Water Resources", in Knox, Joseph B., ed. *Global Climate Change and California: Potential Impacts and Responses.* University of California Press, 1991. p.82.

[120] California Statistical Abstract. Table J-7, "Motor Vehicle License Drivers." January 2001.

[121] California Statistical Abstract. Table J-5, "Registration of Motor Vehicles and Trailers." January 2001.

[122] California Statistical Abstract. Table J-1, "Mileage of Maintained Public Roads." January 2001.

[123] California Statistical Abstract. Table J-6, "Fuel Distributions 1970 to 1999." January 2001.

[124] California Energy Commission Staff Report. "California Energy Demand 2000-2010." Technical Report to California Energy Outlook 2000. Docket #99-CEO-1. June 2000. p.3.

[125] California Energy Commission. "Historical and Forecasted Greenhouse Emissions Inventories for California." September 30, 1997.

[126] California Trade, Commerce, and Technology Agency. "California, An Economic Profile." January 2001.1996 figure: $294 billion. California Trade and Commerce Agency. "California, An Economic Profile." September 1997.

[127] (Ranked as a nation.) California Energy Commission Staff Report. "California Energy Demand 2000-2010." Technical Report to California Energy Outlook 2000. Docket #99-CEO-1. June 2000. p.3.

[128] California Energy Commission, http://www.energy.ca.gov/reports/stats/table58.html (March 4, 1998).

[129] California Energy Commission Staff Report. "California Energy Demand 2000-2010." Technical Report to California Energy Outlook 2000. Docket #99-CEO-1. June 2000. p.3.

[130] California Department of Finance. California Statistical Abstract. Table P-48, "Per Capita Energy Consumption, 1997," Table P-37, Gross State Product, 1998," and Table P-29, Resident Population, July 1, 1999." January 2001.

[131] California Department of Finance. California Statistical Abstract. Table P-48 "Per Capital Energy Consumption, 1997." January 2001.

[132] California Department of Energy. "California's Major Sources of Energy." May 1, 2001 (http://www.energy.ca.gov/html/energysources.html)

[133] California Energy Commission Staff Report. "California Energy Demand 2000-2010." Technical Report to California Energy Outlook 2000. Docket #99-CEO-1. June 2000. P. 4.

[134] California Energy Commission. http://www.energy.ca.gov/reports/stats/table41.html (March 4, 1998)

[135] U. S. Census. "Projections of the Total Population of States: 1995 to 2025." (http://www.census.gov/population/projections/state/stpjpop.txt)

[136] California Energy Commission. "California Historical Energy Statistics." December 16, 1997. (http://www.energy.ca.gov/energy/reports/stats/statistics.html)

[137] There is some overlap in the authority of the various boards, commissions, departments and agencies. For example, The Department of Conservation in the Resources Agency has authority over the "bottle bill" program, but the Integrated Waste Board has authority over solid waste reduction and recycling. The Department of Fish and Game (Resources) regulates oil spill recovery and discharge of wastes into streams, but similar programs are run by the state and regional water quality control boards (Cal EPA).

[138] See: California Resources Agency web site at: http://ceres.ca.gov

[139] See: California Environmental Protection Agency web site at: http://www.calepa.ca.gov

[140] Shogren, Elizabeth. 2001. "Carbon Dioxide Emissions Jump 2.7% in the U.S." *Los Angeles Times*, June 30, 2001.

[141] Franco, Guido. 2001. "An Early Action Proposal for California." California Energy Commission.

[142] California Energy Commission. 1997. "Historical and Forecasted Greenhouse Gas Emissions Inventories for California", Final Draft, September 30, 1997.

IV. Potential Impacts of Climate Change and Variability for California

There are a wide range of potential impacts to California's critically important natural resource systems, economic systems, and ecosystems that may be caused by climate change and variability. This section reviews several key impact areas. It is based on the scientific research available at this time. Additional research will improve our understanding of these and other impact areas.

Water systems are critically important to the economy, the environment, and to human welfare. Climate change and variability will likely impact the timing, amounts, and form of precipitation as well as its quality and uses. The first section therefore considers climate change impacts to this fundamental and critical resource. Potential impacts to natural resource and ecological systems are then examined in Part 2, followed by a review of potential impacts to infrastructure and several economic sectors in Part 3. Finally, the potential implication of climate change and variability on human health in California are considered in Part 4.

Part 1. California's Water Systems and the Potential Impacts of Climate Change and Variability

Introduction

California's water systems underpin both the state's vibrant economy and the valuable and diverse ecosystems that support it. Climate change and variability will likely impact these critical systems in a number of ways. The report of the water sector assessment team of the national assessment, *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States* (hereinafter "Water Sector Report") notes: "More than twenty years of research and more than a thousand peer-reviewed scientific papers have firmly established that a greenhouse warming will alter the supply and demand for water, the quality of water, and the health and functioning of aquatic ecosystems."[1] Maurice Roos, California's State Hydrologist for decades, reaches a similar conclusion: "Climate change has the potential of affecting a wide variety of water resource elements. These range from water supply, hydroelectric power, sea level rise, more intense precipitation events, water use, and a number of miscellaneous items which include water temperature changes."[2]

This section is divided into three parts. First, it outlines the key features of the California's water systems and infrastructure. Second, it reviews what is known about potential impacts of climate change on these systems. In the third part, it sets forth response strategies for coping and adaptation to potential changes due to climate in the context of existing policy and management

challenges. It also presents research priorities to support informed investments and decision-making in the future. A detailed research agenda is also included in the appendix.

Water Units

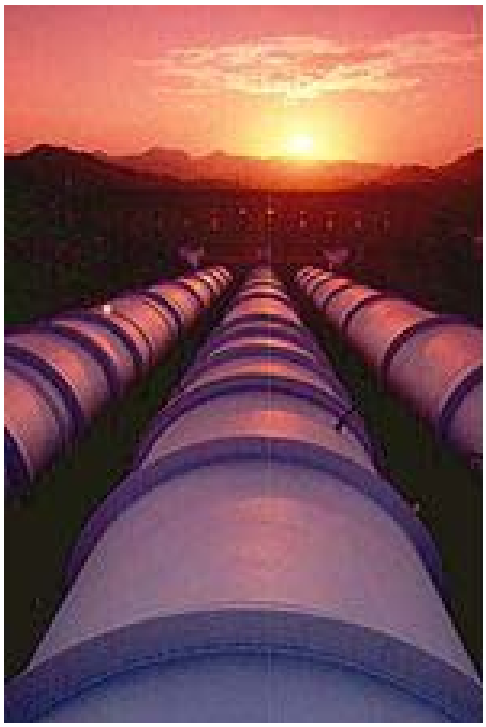
Units of measurement are generally cited here in the units of common usage rather than metric units. The reason for using "barbaric" units is simply that they are more intuitive and understandable to a broad range of readers, whereas metric units such as cubic meters have little meaning to many people. An important objective of this assessment process is that it be useful to stakeholders beyond the scientific community. For those who wish to convert the units, a full conversion table is provided in the appendix.

The common unit for water supply in the U.S. is an "acre-foot" (AF). An acre-foot of water is the volume of water that would cover one acre to a depth of one foot. An acre-foot equals 325,851 gallons, or 43,560 cubic feet, or 1,233.65 cubic meters. Wastewater is typically measured in "million gallons per day" (MGD). One acre-foot equals 0.325851 MG. Figures have usually been converted to AF to provide consistency. One MGD equals 1,120 AF per year, and one AFY equals 0.000893 MGD.

California's Water Systems and Infrastructure

Water is critically important to California's economic productivity, quality of life, and natural systems. Its scarcity or abundance – in place and time – have historically created opportunities, wealth, environmental impacts, and conflicts. The contests between north and south, cities and farms, environmentalists and developers, sportsmen and hydrologic engineers have dominated water policy. The squabbling has gone on since before statehood, and current disputes indicate that the issues have not receded.[3]

An elaborate system of reservoirs, canals, aqueducts, and other engineered facilities in California are matched only by the even more elaborate set of laws and policies that govern the state's most controversial resource. The disparities between the geography of water availability and the desire for water in California spawned an unprecedented control of natural systems. The diversion, conveyance, and storage systems developed in California in the 20th century, including the Central Valley Project, the State Water Project, the Colorado River Aqueduct, and the Los Angeles, San Francisco, and East Bay Aqueducts, are remarkable engineering accomplishments.[4] These water works move millions of acre-feet of water around the state annually. The state's 1,200-plus reservoirs have a total storage capacity of more than 42.7 million acre feet (maf).[5]



Three Major Sources of Water Supply

California has three principle sources of water supply. They are: 1) surface water, which is often diverted or extracted and stored in reservoirs, 2) groundwater, and 3) imported supplies, (mainly from the Colorado River). Conjunctive use of surface and groundwater, re-use of agricultural and urban water, inflow from Oregon, and other factors make precise accounting for water supplies a complicated task. Each of the three main sources are outlined in general figures below. Water supplies are usually represented in amounts per year. Generally, the reference is to the *water year*.

The "Water Year"

The Department of Water Resources, the U.S. Geological Survey, and other water management agencies report hydrologic data on a “water year” basis. The water year extends from October 1st through September 30th.

Though the average precipitation in California is about 193 million acre feet per year (mafy), the variability is extremely large.[6] The water supply and extraction is as follows:

Average Annual Water Supply and Extractions From All Sources[7]
(average annual figures in million acre feet per year)

Water Source	**(mafy)**
precipitation	193.0
natural recharge, percolation, and non-developed uses[8]	122.0
surface runoff[9]	70.8
(historical range: 15 mafy (1977) to 135 mafy (1983))[10]	
"average annual water supply"[11]	85.0
total groundwater resources[12]	850.0
economically recoverable groundwater resources[13]	250.0
extractions of surface water[14]	21.6
extractions of groundwater[15]	15.0
"net" use of groundwater ("use" plus overdraft)	8.4
"use" of groundwater (does *not* include overdraft)[16]	7.1
overdraft[17]	1.3
surface storage capacity (reservoirs)[18]	42.8
delta extractions[19]	10.3
reclaimed water	0.2
desalination[20]	0.017
Imported Water	
Colorado River imports (entitlement is 4.4 mafy)	5.2
"local imports"	1.0

A Stressed Water System

Every *major* water supply source in California is currently *over-allocated*. This means that the systems are beyond their physical and/or legal capacity to be sustained. In a systems sense, they are in overshoot. For example, court decisions on Mono Basin diversions, and more recently on the Owens River and Owens Lake, restrict the diversion of water to Los Angeles in order to restore environmental damage.[21] The Sacramento-San Joaquin River Delta problems stem from diversions above the delta and from extractions for the State Water Project, the Central Valley Project. Other contributing factors to extensive environmental damage include agricultural runoff, invasive species, land-use practices, and over-fishing.

For many years, demands have been made on water systems throughout the state that have insufficient flows to meet everyone's desires. As a result, eighty to ninety percent of the state's

riparian habitat has been lost, and ninety-seven percent of the salmon and steelhead spawning habitat has been lost.[22] Ninety-five percent of the state's wetlands have already been destroyed,[23] and the largest wetland in the western U.S., the San Francisco Bay-Delta, is the subject of a major water policy controversy. Legal mandates for restoration of the system from Congress (e.g. the *Central Valley Project Improvement Act* [24]), and requirements to comply with various laws including the *Endangered Species Act* (ESA), are driving an extensive evaluation of water management.

A state/federal process known as CALFED is currently seeking to develop a process to manage key water systems within their limits.[25] The Colorado River, an important source of water for California, is also heavily over-appropriated. The river rarely reaches the sea since completion of Glen Canyon Dam. California has a normal year allocation of 4.4 mafy, but it has been taking 5.2 mafy (the 4.4 mafy plus "surplus" water that has been declared available in the past).[26] The state is working on a plan dubbed the "4.4 plan" (now officially called the "California Water Use Plan for the Colorado River") to live within its allocation, or "normal year apportionment" per the agreement. California has agreed to reduce its take to 4.4 mafy over the next decade and a half. Finally, groundwater is a major source of water in California. Overdraft and contamination has reduced the availability of groundwater supplies throughout the state, and salt water intrusion in coastal aquifers is already a problem in some coastal areas.[27]

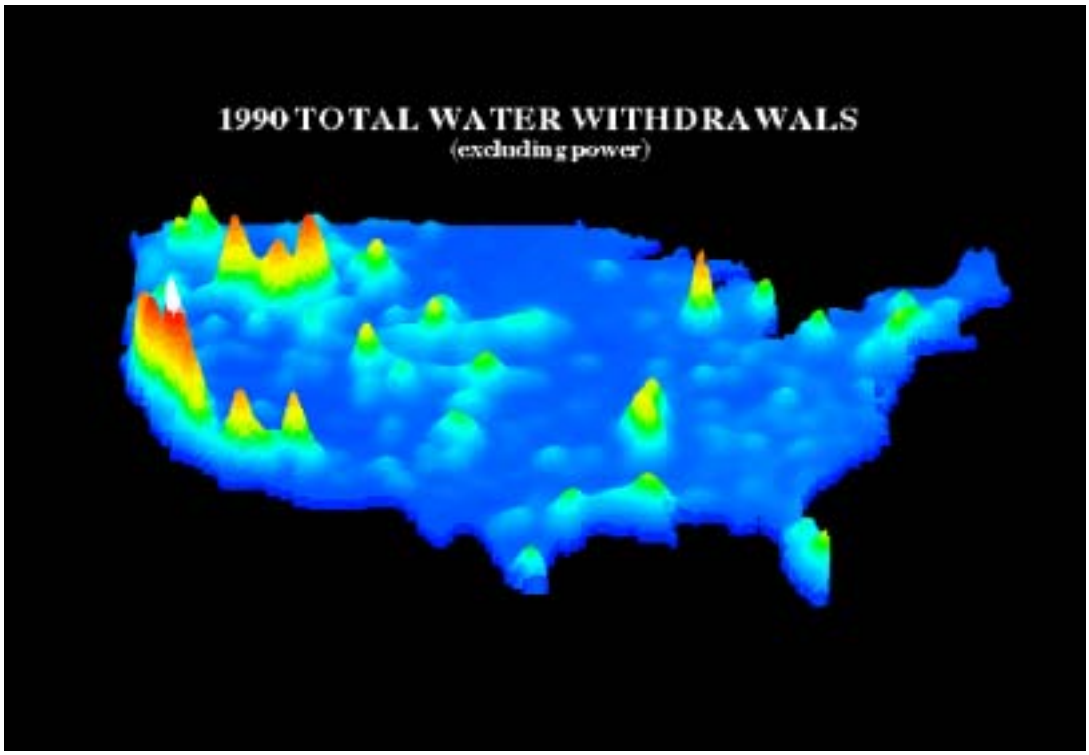
With very real limits to the state's water systems, and every major supply source being *reduced* by legal and/or physical constraints, the state's water systems may be fairly said to be stressed. As a consequence of past water management practices and other factors, the state is now working to restore some of the devastation of aquatic, riparian, and wetland ecosystems. The stresses already in place, however, are causing the list of threatened and endangered species to continue to grow. California has the most threatened and endangered species listed in the 48 contiguous states.[28]

Water Use

California extracts large amounts of water from natural systems to use for urban, industrial, and agricultural purposes.

Source: Charles Burt, 2002. Irrigation Training and Research Center (ITRC), BioResource and Agric. Engr. Dept CAL POLY, SLO www.itrc.org Presentation to DWR Bulletin 160-03 Advisory Committee.

As the map below indicates, California's withdrawals exceed all other regions of the country.



USGS, Water Use in the United States, http://water.usgs.gov/watuse/graphics/wuto.fact.3d.gif

Water use in the urban sector has been increasing, while agricultural demand peaked at the end of the 1980s and is declining. Agriculture uses about 80 percent of the water that is diverted and extracted or imported to California. The water is used primarily to irrigate pasture and croplands. Alfalfa and irrigated pasture are the two largest water-using crops in California. In the early 1970s, agriculture used about 85 percent of the state's developed water.[29] In 1980, agriculture used approximately 83 percent of the state's developed supply,[30] and by the end of the 1980s, the percentage had fallen to below 80 percent.

California's Top Water Users

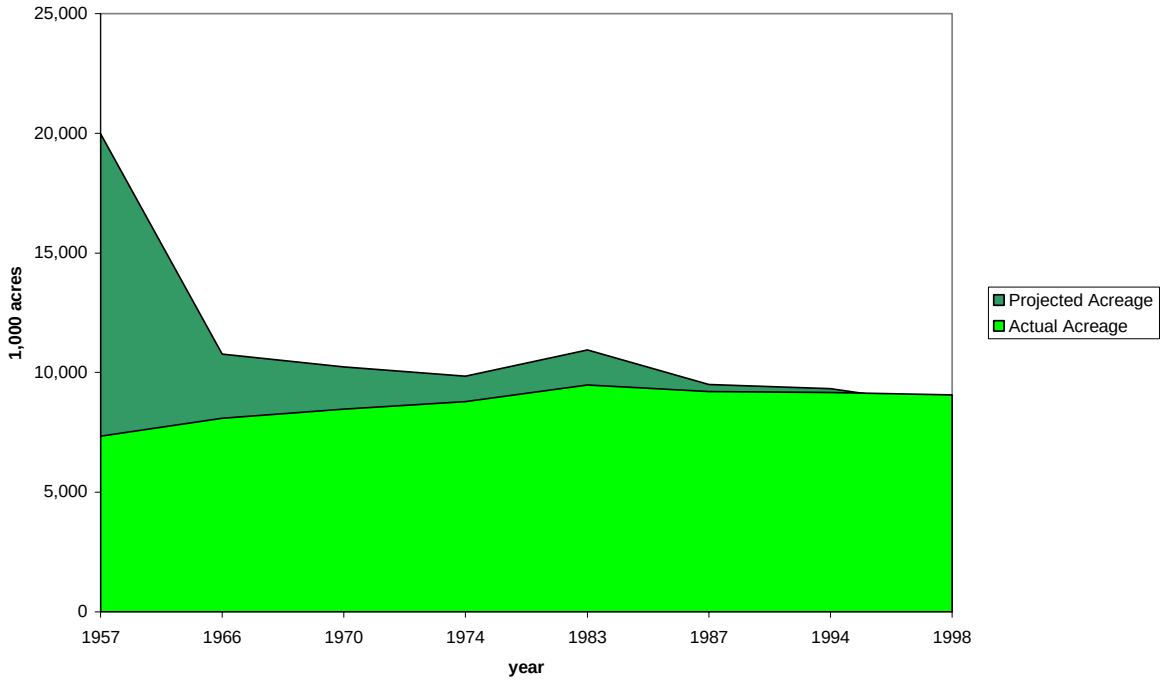
Alfalfa and irrigated pasture are the top water consuming crops in California, according to DWR's *State Water Plan* Bulletin 160-98. Alfalfa receives up to 10 acre feet of water per acre per year (afy), with pasture close behind at about 9.5 afy per acre.[31] The applied water actually evaporated and transpired (ETAW) by these two crops is also the largest of any crop grown in California by a wide margin (up to 7 afy per acre for alfalfa and 6.75 afy for pasture). DWR indicates that 1,094 acres, over 10 percent of California's irrigated cropland, is devoted to alfalfa. Pasture is the third largest irrigated area at 933 acres.[32] The combination of the area irrigated and the large amounts of water used makes these low-value crops the state's largest users.

The total amount of land being irrigated, and the amount of water used for irrigation, peaked in the 1980s.[33] Irrigated land area increased from about 4 million acres in 1930 to a high in 1981 of 9.7 million acres.[34] Projections by DWR for continuing increases in water used for irrigation have been replaced with forecasts for declining water use for agriculture.[35] Currently about 9.5 million acres are irrigated, counting multiple cropping. (Approximately 9.1 million acres plus 0.4 million acres of multiple cropping.)[36]

Irrigation techniques vary widely.

Source: Charles Burt, 2002. Irrigation Training and Research Center (ITRC), BioResource and Agric. Engr. Dept CAL POLY, SLO www.itrc.org Presentation to DWR Bulletin 160-03 Advisory Committee.

Actual and Projected Irrigated Acreage in California



Source: Author, based on data from state water plans in table below.

Irrigated Land Area in California
Actual and Projected Area in DWR Bulletin 160 Series [37]

(1,000 acres)

	Report Year							
	1957	**1966**	**1970**	**1974**	**1983**	**1987**	**1994**	**1998**
Year Projected *(actual figures in bold)*								
1950	**7,346**	--	--	--	--	--	--	--
1960	--	**8,085**	--	--	--	--	--	--
1967	--	--	**8,480**	--	--	--	--	--
1972	--	--	--	**8,780**	--	--	--	--
1980	--	--	--	--	**9,490**	--	--	--
1985	--	--	--	--	--	**9,200**	--	--
1990	--	9,564	9,340	9,740	9,850	--	**9,178**	--
1995	--	--	--	--	--	--	--	**9,068**
2000	--	--	--	--	10,030	--	--	--
2010	--	--	--	--	10,220	--	--	--
2020	19,176	10,775	9,640	9,850	--	--	8,800	8,635

The state's water systems have helped make the Central Valley one of the world's most productive agricultural regions. Parts of the valley are virtually a desert based on precipitation levels; Bakersfield receives about six inches a year and Fresno less than twelve inches, while the annual average evaporation potential in the Valley exceeds 60 inches.[38] Much of the Valley, from the far southern reaches to the north, was historically a string of shallow lakes and wetlands due to runoff from the Sierra Nevada. Of the 9.5 million acres irrigated in California, seven million are in the Central Valley.[39]

The California experience in irrigated area and water use is part of (and a contributor to) a national trend. The amount of irrigated land nationwide peaked in 1978 and has declined an average of seven percent per year.)[40] Water used for irrigation peaked in California in the early 1980s. U.S. irrigation figures leveled out around 1980.[41] It is reasonable to conclude that the amount of water dedicated to irrigation will continue to decline. Land retirement, crop shifting, water transfers, and improved efficiencies in irrigation, conveyance and management will all contribute to a decline in water used for irrigation.[42]

Total extractions from the state's natural water systems has increased through the past century and a half, with flows for the environment declining and becoming more polluted as a result. Henry Vaux provided the following sobering assessment of California's water situation in a survey of the potential implications of climate change in 1991:[43]

> Today California's water economy is not in good shape. Even in average years, water supplies are balanced with water use only because of groundwater mining, a practice that cannot be sustained indefinitely.

Vaux was commenting at about the time that California's last major drought was ending. In that year, the State Water Project delivered only about 0.5 million acre feet, its lowest deliveries ever. Some farmers received no deliveries from major suppliers, and urban areas were forced to ration deliveries. Since the drought ended, and even with above-average precipitation in a number of years, groundwater overdraft persists.

The urban water use sector, accounting for about 20% of the developed water use in the California, includes residential uses, commercial, industrial, and institutional uses, and municipal uses such fire fighting. Urban uses of water have been increasing, both as a percentage of total extractions and in absolute terms, throughout this century. While urban water use is growing as population and the economy grows – per-capita water use has been declining statewide since the late 1980s. Water use efficiency has increased dramatically in many urban areas. Data for the second half of the 1900s is presented below. The table indicates both the official DWR forecasts and the actual levels of use (in bold).

Urban "Demand" Projections
"Applied Water"
in DWR's Bulletin 160 Series [44]

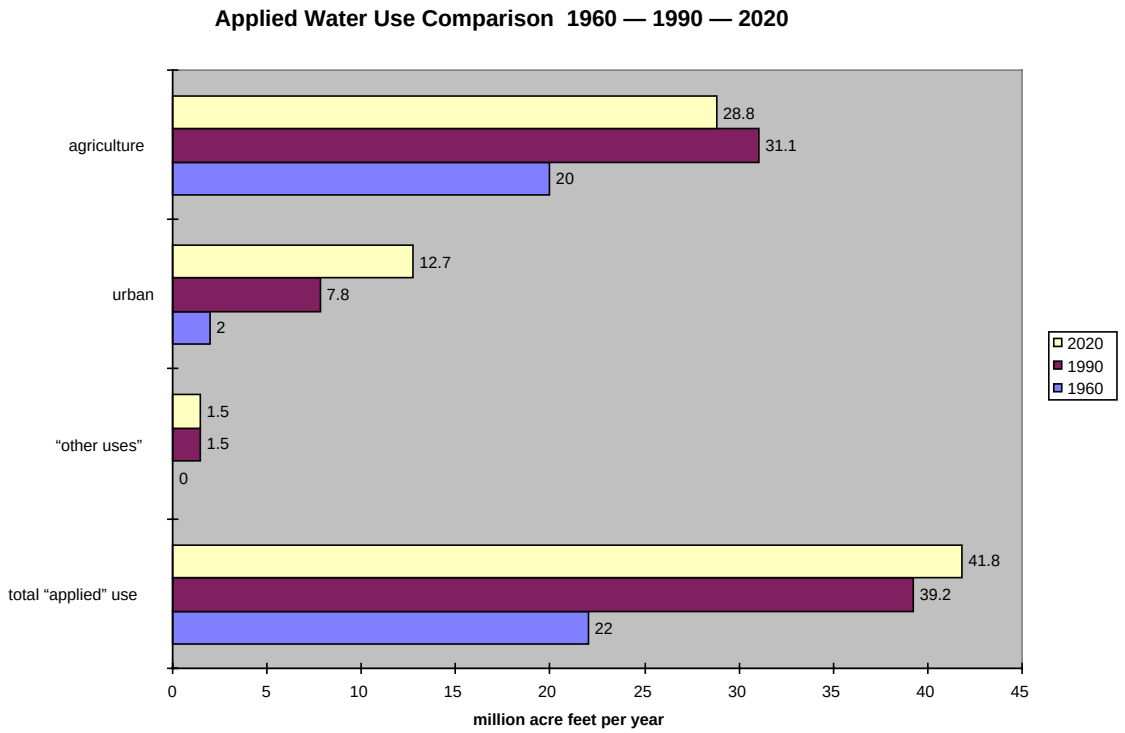
	Report Year							
	1957	**1966**	**1970**	**1974**	**1983**	**1987**	**1994**	**1998**
Year Projected *(actual figures in bold)*								
1950	**1,656**	--	--	--	--	--	--	--
1960	--	**3,257**	--	--	--	--	--	--
1967	--	--	**4,380**	--	--	--	--	--
1972	--	--	--	**5,040**	--	--	--	--
1980	--	--	--	--	**5,762**	5,860	--	--
1985	--	--	--	--	--	**6,590**	--	--
1990	--	8,480	7,370	6,400	6,600	--	**7,800**	--
1995	--	--	--	--	--	--	--	**8,770**
2000	--	--	--	--	7,265	--	9,300	--
2010	--	--	--	--	8,070	8,710	10,900	--
2020	8,301	14,000	11,840	9,730	--	--	12,700	12,020

The following table of data from DWR indicates total water use in 1960, 1990, and forecasts for 2020.

Total Water Use Comparison[45]

	1960[46] (mafy)	**1990**[47] (mafy)	**2020**[48] (mafy)
urban	2.0	7.8	12.7
agriculture	20.0	31.1	28.8
"other uses"	0.0	1.5	1.5
total "applied" use	**22.0**	**39.2**	**41.8**
designated env. flows	1.0	28.8	29.3
other environment	62.0	15.5	11.8
total environment[49]	**63.0**	**44.3**	**41.1**
population (million)[50]	**15.7**	**30.0**	**48.9**
irrigated acreage[51]	**7.5**	**9.18**	**8.8**

The following graph illustrates the changes that have occurred and are anticipated in water uses over the 1960-2020 time frame.



Source: California Department of Water Resources. *California Water Plan Update*, Bulletin 160-93. 1994.[52]

Note that total applied water use in California almost doubles (with most of the increase in the first period), while total environmental water declines by a third.

Total "Applied" and "Environmental" Use

	1960[53]	**1990**[54]	**2020**[55]
total "applied" use	22.0	39.2	41.8
total environment	63.0	44.3	41.1

The national trend is similar to California, as efficiency improvements are more broadly implemented. Wayne Solley at USGS provides the following account:

Changes in U.S. Water Use: 1950-1995

Wayne Solley, et al., USGS[56]

The general increase in water use from 1950 to 1980 and the decrease from 1980 to 1995 can be attributed, in part, to the following major factors:

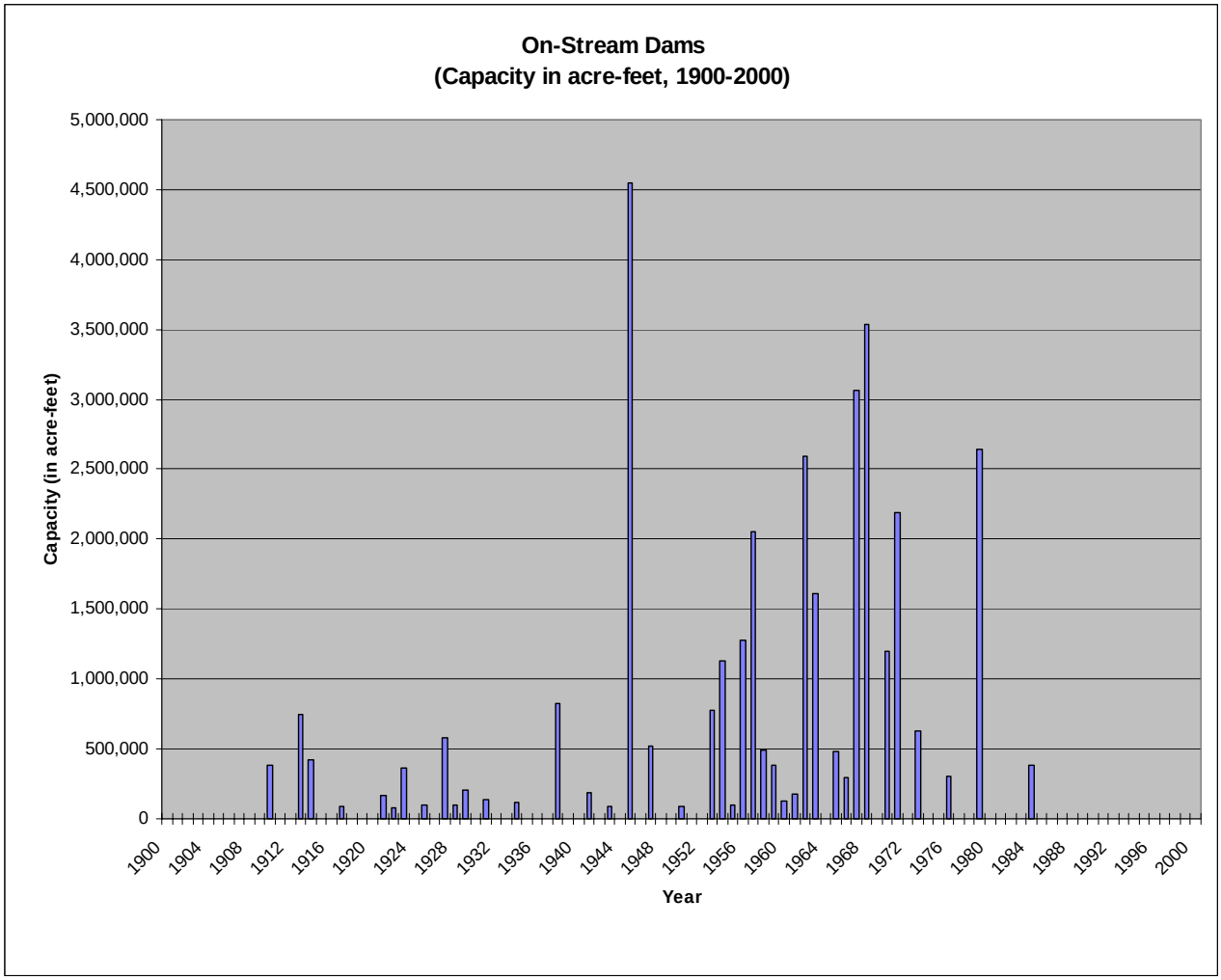
- Most of the increases in water use from 1950 to 1980 were the result of expansion of irrigation systems and increases in energy development.
- The development of center-pivot irrigation systems and the availability of plentiful and inexpensive ground-water resources supported the expansion of irrigation systems.
- Higher energy prices in the 1970's, and large drawdown in ground-water levels in some areas increased the cost of irrigation water. In the 1980's, improved application techniques, increased competition for water, and a down-turn in the farm economy reduced demands for irrigation water.
- The transition from water-supply management to water-demand management encouraged more efficient use of water.
- New technologies in the industrial sector that require less water, improved plant efficiencies, increased water recycling, higher energy prices, and changes in laws and regulations to reduce the discharge of pollutants resulted in decreased water use and less water being returned to the natural system after use.
- The enhanced awareness by the general public to water resources and active conservation
- programs in many States have contributed to reduced water demands.

Surface Water Storage: Dams in California

Development of reservoir capacity in California in this century has followed a revealing pattern. Prior to 1940 approximately 6 million acre feet of capacity (31 dams of over 50,000 acre feet capacity) was developed, two thirds of which was local (26 dams) and one third federal (5 dams). In the 1940s 3 federal dams accounted for about 5 million acre feet, while 3 local dams provided less than half a million acre feet. The 1950s brought another 5 million acre feet in 8 federal dams and over a million in 11 local dams. In the 1960s 8 more federal dams provided a little over 4 million acre feet, 17 local dams provided a little over two million more, and 6 state dams provided 5 million more for the all time record of just under 12 million acre feet of capacity in a decade. The 1970s saw a decline to just over 6 million acre feet again, with 6 federal dams providing about 2.5 million acre feet, 3 local dams at slightly more, and 4 state dams at about

one million. In the 1980s, less than half a million acre feet was added by one federal dam. There were no local or state additions of over 50,000 acre feet.[57] In the 1990s MWD built a major off-stream storage facility, the Diamond Valley Reservoir in the Los Angeles Basin.

The following graph indicates the scale and timing of dam development in California.



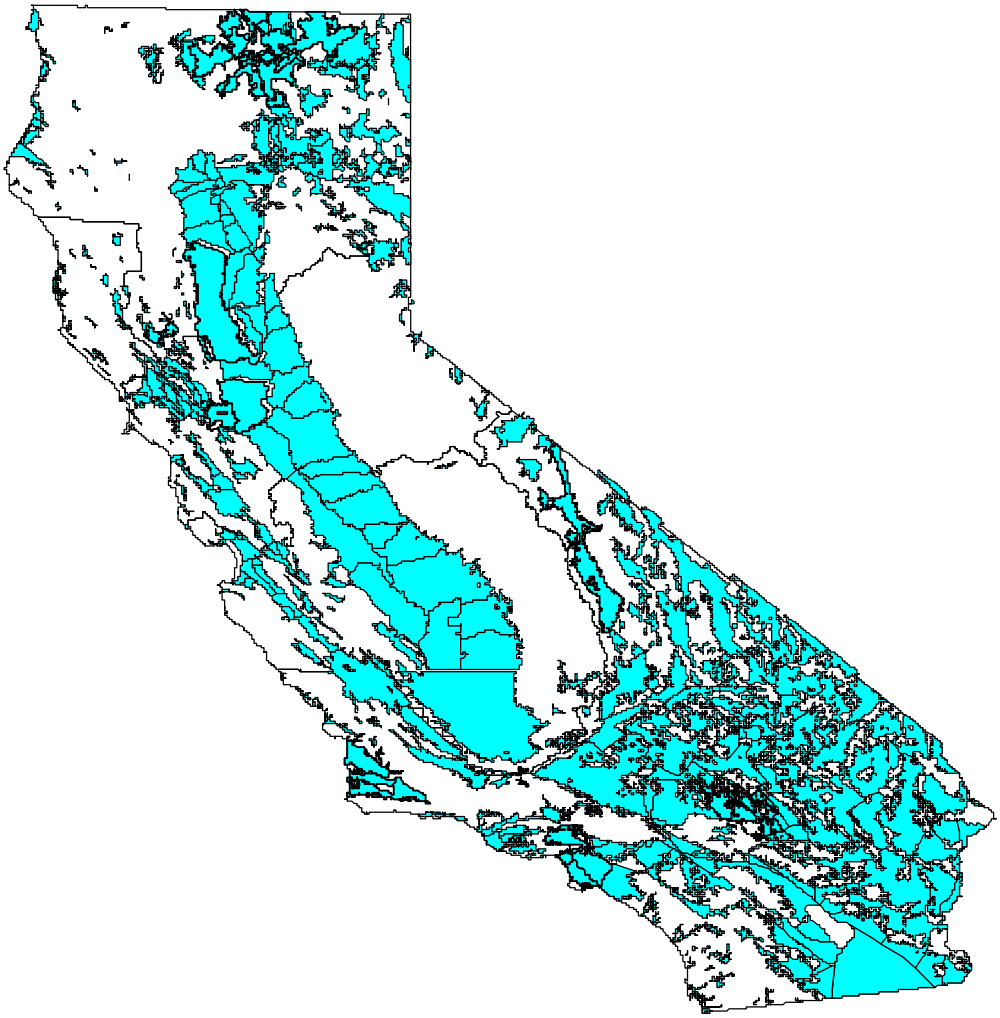
Source: California Department of Water Resources, Bulletin 160-87, *California Water: Looking to the Future*, November 1987. (No new on-stream dams have been built in California since the 1980s.)

Groundwater Systems in California

Groundwater supplies about one third of the state's average use. California overdrafts groundwater at levels of about 2 mafy, and in severe drought years it may be as high as four to 10 maf.[58] The following map displays the major basins in the DWR's Bulletin 118.

California's Groundwater Bulletin 118 - Update 2002

Digital Basin Coverage

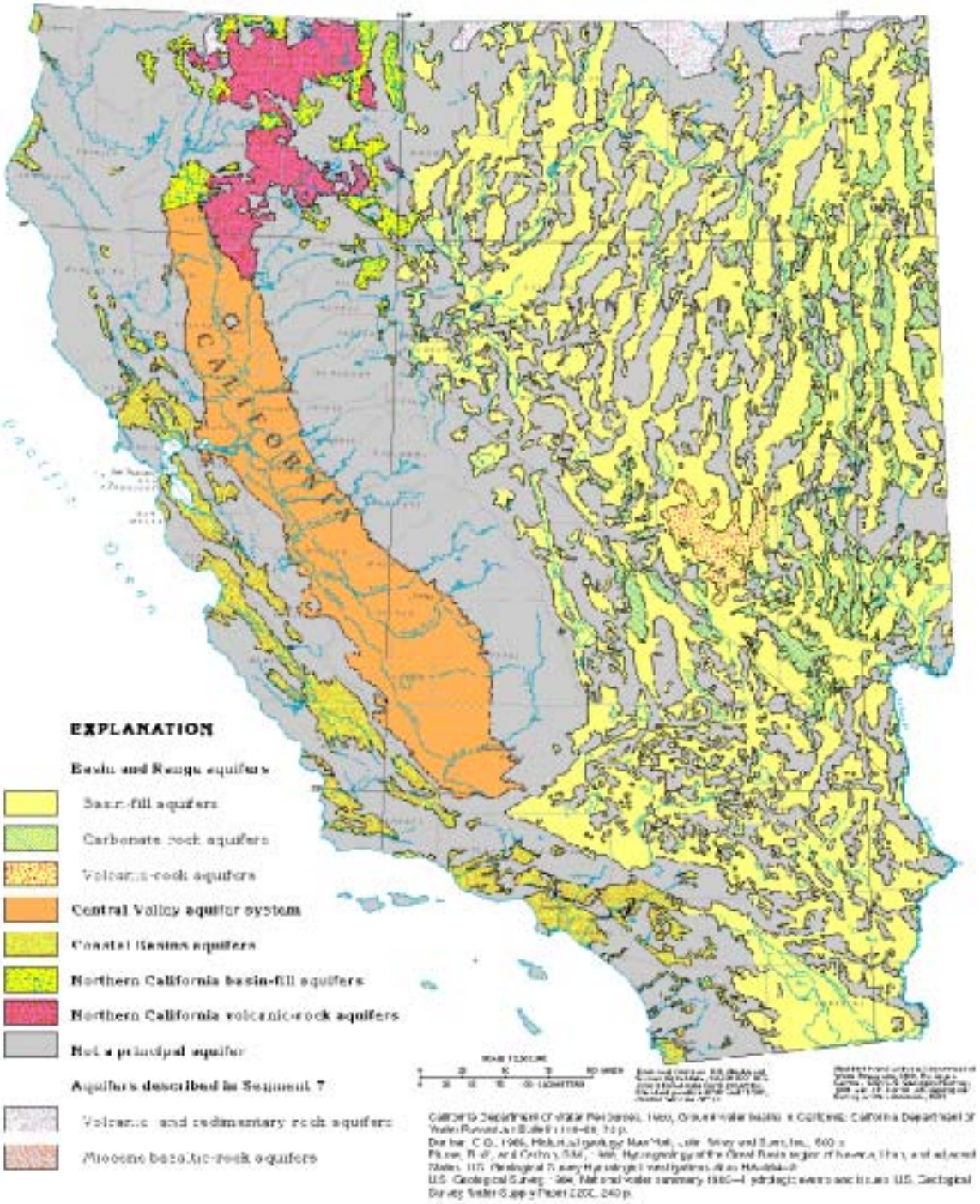


Source: Rob Swartz, California Department of Water Resources,
California's Groundwater Bulletin 118 - Update 2002, April 12, 2002

The USGS groundwater map for California and Nevada from the *Ground Water Atlas of the United States* is reproduced below.

USGS Groundwater Map of California and Nevada

Figure 11. The aquifers in Segment 1 have been grouped into the major aquifers or aquifer systems. Although four of the aquifers consist of basin-fill deposits, the characteristics of these deposits vary, depending on differences in geology, physiography, and climate.

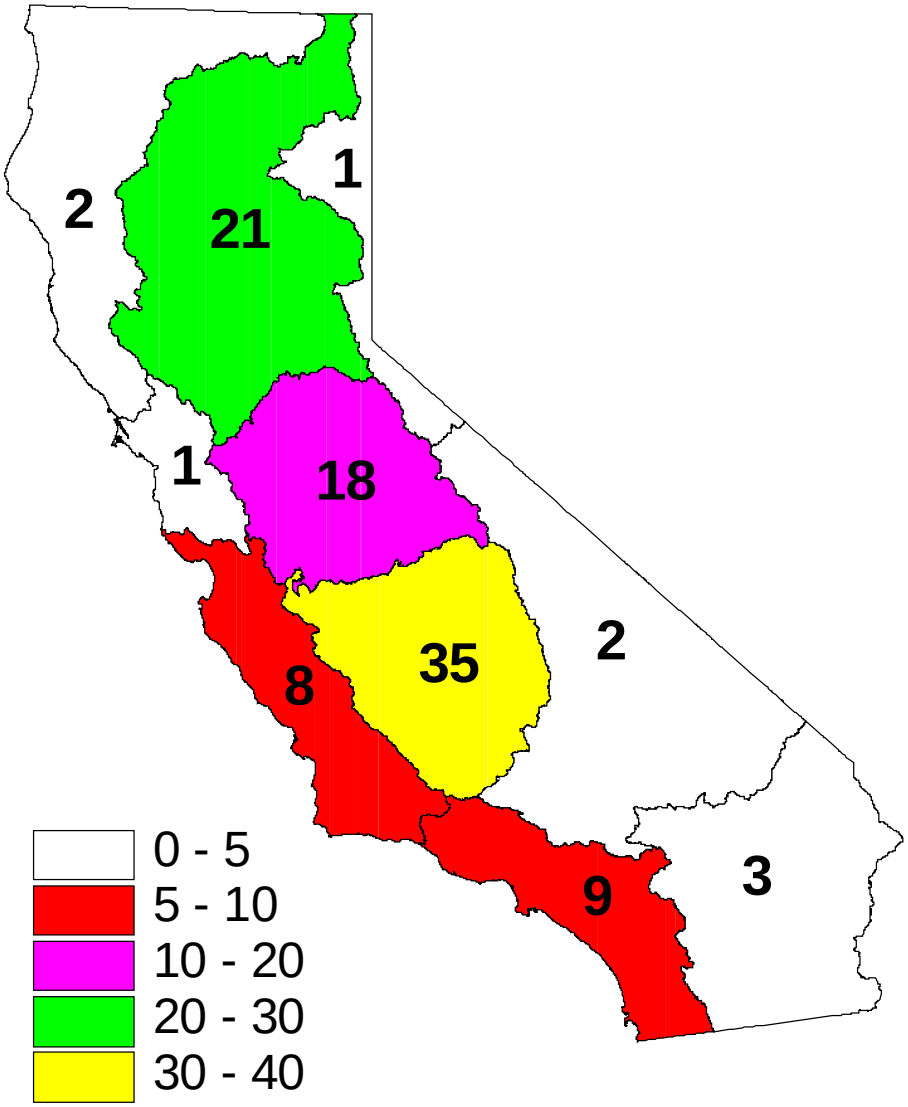


Source: USGS, *Ground Water Atlas of the United States*, California, Nevada HA 730-B, http://capp.water.usgs.gov/gwa/ch_b/gif/b011.gif

Groundwater use by hydrologic region is displayed in the following map.

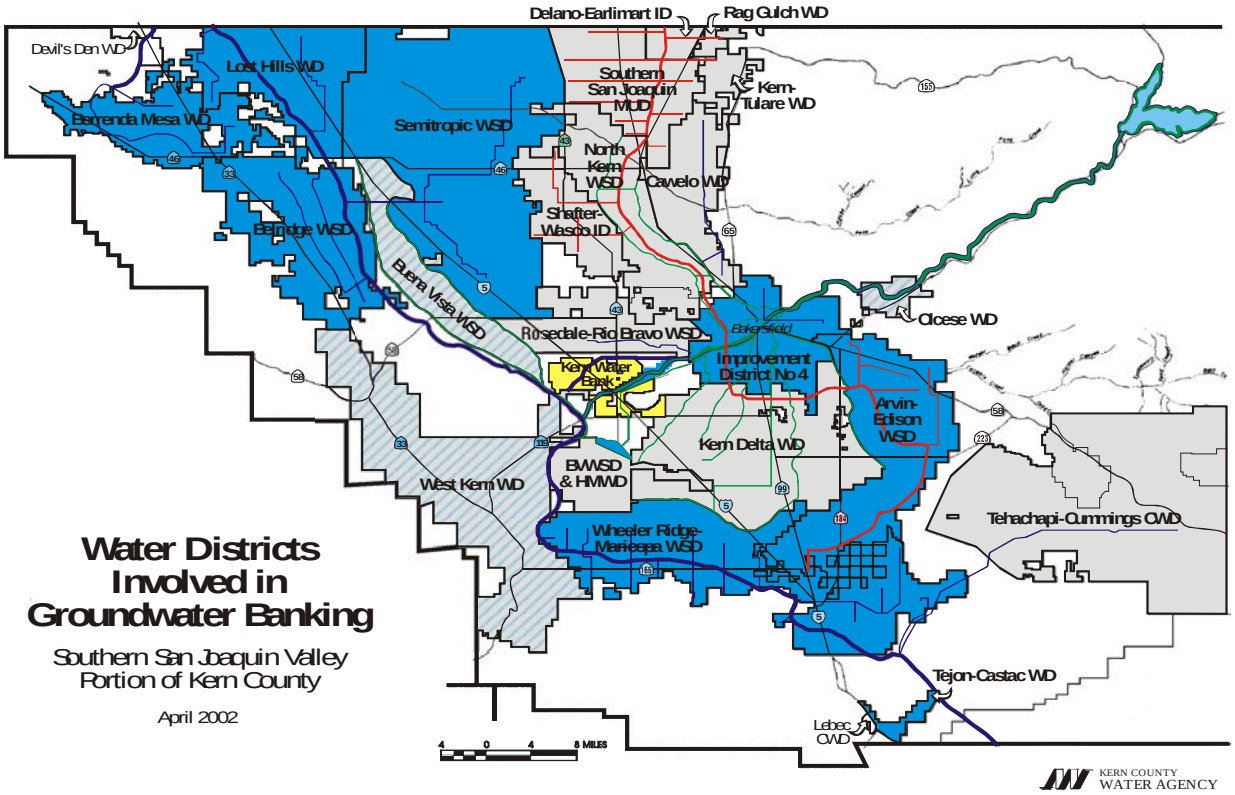
Urban and Agriculture Groundwater Use by Hydrologic Region

(Percent of total average annual groundwater extraction.)



In the southern San Joaquin Valley, water banking projects have been developed to store water for extraction and use locally and in other areas.

Southern San Joaquin Valley Water Districts Involved in Groundwater Banking



Source: Lloyd Fryer, 2002. Kern County Water Agency, Presentation to DWR Bulletin 160-03 Advisory Committee.

The following table indicates some of the groundwater banking projects and the amounts of water involved.

Kern County Water Agency
Groundwater Banking Projects[59]

Project	Gross Area (Acres)	Date Operational	Capital Cost ($)	Maximum Annual Recovery (AF)	Maximum Annual Recharge (AF)	Estimated* Defined Storage (AF)
Direct Recharge Projects						
Berrenda Mesa	369	1983	3,318,000	46,000	58,000	200,000
COB 2800 Acres	2,760	1978	8,350,000	46,000	168,000	800,000
Kern Water Bank	19,900	1995	77,100,000	287,000	450,000	1,000,000
Pioneer	2,253	1995	19,902,000	98,000	146,000	400,000
West Kern WD/Buena Vista WSD	2,000	1978	8,000,000	45,000	70,000	250,000
Subtotal	**27,282**		**116,670,000**	**522,000**	**892,000**	**2,650,000**
In Lieu/Direct Recharge Projects						
Arvin-Edison/Metropolitan WD	130,000	1998	25,000,000	40,000	140,000	250,000
Semitropic WSD/MWD et al	221,000	1990	134,000,000	223,000	315,000	1,000,000
Subtotal	**351,000**		**159,000,000**	**263,000**	**455,000**	**1,250,000**
TOTAL	**378,282**		**275,670,000**	**785,000**	**1,347,000**	**3,900,000**

Estimated storage is based on historic activities or is defined contractually.

Water Supply Reductions

Water supplies from all major sources in California are *decreasing* by significant amounts. The causes of these reductions in extractions are primarily socially determined limitations based on biological and physical factor. For example, water extractions are limited by court decisions and legislation due to unacceptable environmental damage. In some cases, such as siltation or salt water intrusion, the reductions are due to a combination human actions and natural forces. In others, such as chemical contamination of surface and groundwater resources, the cause is clearly human activity.

Combined reductions of diversions from the Eastern Sierra by Los Angeles due to the Mono Lake decision[60] and the Owens Valley pumping restrictions are estimated at 0.28 mafy.[61] Total reductions in extractions from the Delta (including CVPIA compliance, delta accord agreements, reductions from upstream diverters, Shasta Dam operations, Trinity River, and others) are in the range of 1 to 3 mafy.[62] Eliminating groundwater overdraft will require reductions in extractions of an additional 1.3 mafy.[63] Finally, the Colorado River supply reduction from the 5.2 mafy that California is currently taking to 4.4 mafy will involve a reduction of 0.8 mafy.[64]

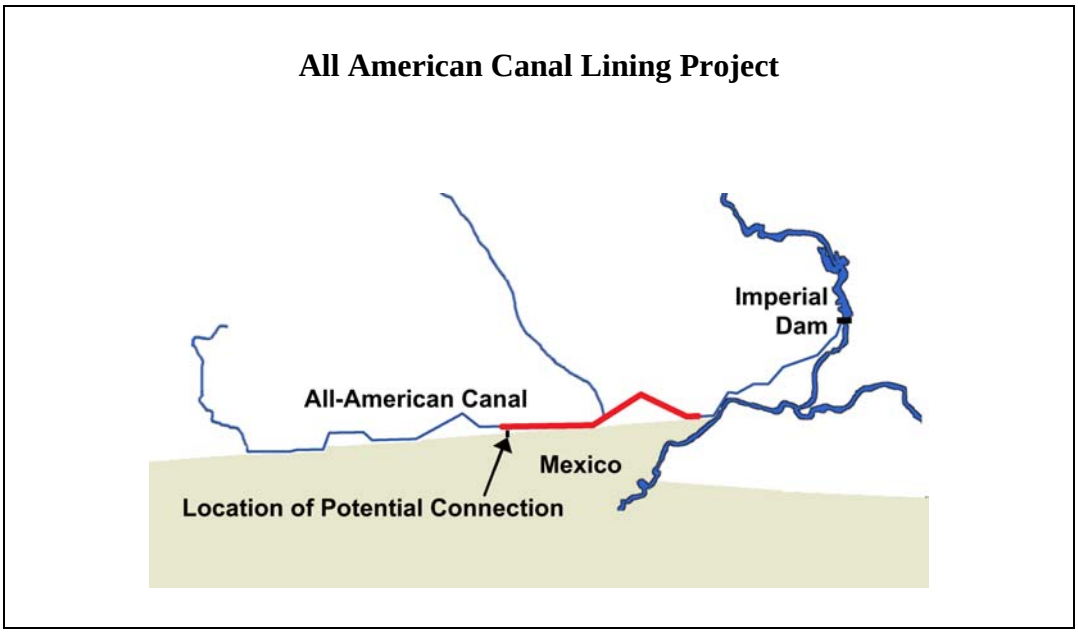
Water Supply Additions

New additions to the state's water supplies have been made in recent years, although they are coming from unlikely sources. The first "new supply" is structural efficiency improvements, such as loss-reduction from conveyance and delivery systems, and end-use improvements in water service delivery. Measures such as lining IID's canal to reduce conveyance losses (estimated at a savings of 0.1 mafy[65]) appear promising.

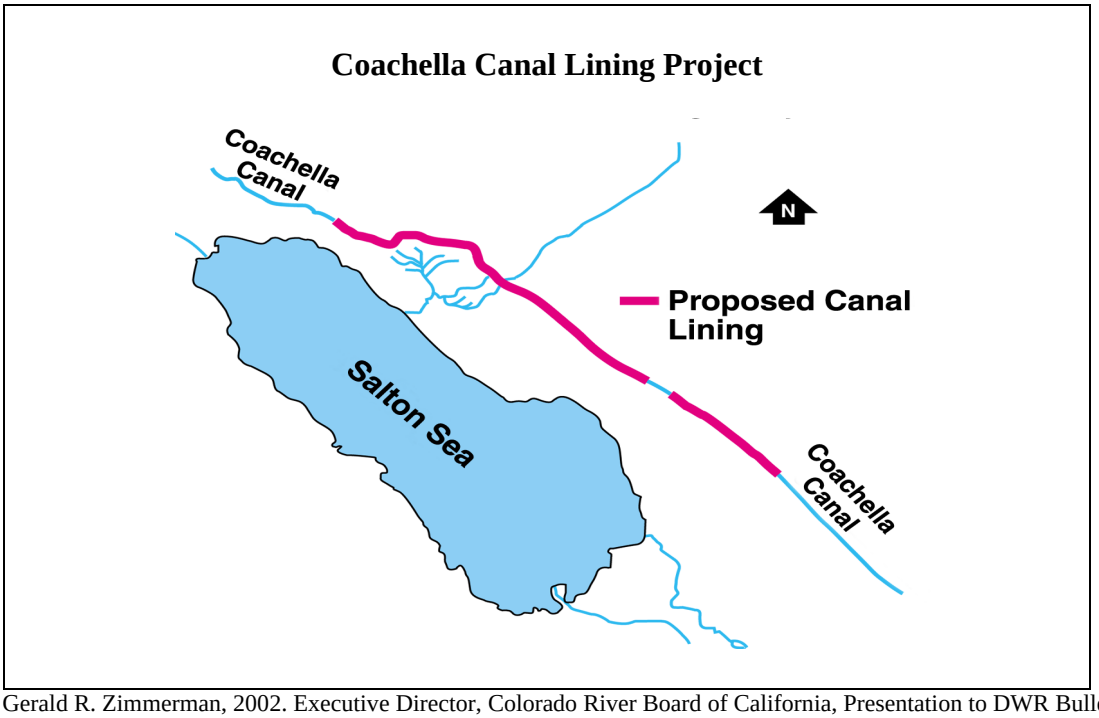
Several canal lining program are planned for the Colorado River water supply systems.

Colorado River Transfer and Conservation Programs[66]

MWD/IID Transfer	110,000 af/yr
SDCWA/IID Transfer	200,000 af/yr
CVWD/IID Transfer	100,000 af/yr
Canal seepage conservation programs	94,000 af/yr



Source: Gerald R. Zimmerman, 2002. Executive Director, Colorado River Board of California, Presentation to DWR Bulletin 160-03 Advisory Committee.



Source: Gerald R. Zimmerman, 2002. Executive Director, Colorado River Board of California, Presentation to DWR Bulletin 160-03 Advisory Committee.

Other measures, such as urban water conservation, are estimated to save 1.0 mafy, and reclamation is expected to provide another 0.5 mafy by 2020.[67] Potential sources such as desalination are currently not expected to deliver significant volumes of new water due to their high capital and operating costs.[68] Costs are coming down, however, and MWD has issued an RFP to develop seawater desalination in its service area – up to 50,000 AF. New technology has reduced costs considerably, especially for brackish water groundwater desalination.

Inter-basin Transfers and Major Water Supply Systems in California

Major inter-basin water transfers in California began at the turn of the 20th century. Early transfers, such as the Colorado River diversions to the Imperial Valley, were gravity fed and therefore required no energy for pumping. The Los Angeles aqueduct from the Mono Basin and Owens Valley in the Eastern Sierra, San Francisco's water from Hetch Hetchy Valley (in Yosemite National Park), and the CVP are *net energy producers* due to the drop in elevation and the hydro-power production of the systems. Systems built later in the century, however, required significant pumping plants and energy inputs to lift water over mountain ranges. The State Water Project and the Colorado River Aqueduct are the two most energy-intensive systems in the state.

Watersheds and Basins

Water flows by gravity from a geographic high point to the sea or to saline sinks within *watersheds* or *drainage basins*. These basins or watersheds may in turn be considered cascading units where one watershed, say a mountain valley, flows into a larger watershed or basin, such as the Central Valley. When water is moved from one basin to another through artificial means (aqueducts) it is an inter-basin transfer.

The State Water Project

The State Water Project (SWP) was built and is managed by the California Department of Water Resources (DWR). It provides water for agricultural and urban uses.[69] SWP facilities include 28 dams and reservoirs, 22 pumping and generating plants, and nearly 660 miles of aqueducts.[70]

The SWP extracts water from the Delta at several points. Upstream, the state has water rights on the Feather River in Northern California, which provides about 25% of the water the state extracts from the delta. Lake Oroville, the project's largest storage facility, has a total capacity of about 3.5 million acre-feet. Three smaller upstream reservoirs provide additional storage.[71] (Oroville Dam is the tallest and one of the largest earth-fill dams in the United States.)[72] Power is generated at the Oroville Dam as water is released down the Feather River, which flows into the Sacramento River, through the Sacramento-San Joaquin Delta, and to the ocean through the San Francisco Bay.

Water is pumped out of the delta for the SWP at two locations. In the northern Delta, Barker Slough Pumping Plant diverts water for delivery to Napa and Solano counties through the North Bay Aqueduct.[73] Further south at the Clifton Court Forebay, water is pumped into Bethany Reservoir by the Banks Pumping Plant. From Bethany Reservoir, the majority of the water is conveyed south in the 444-mile-long Governor Edmund G. Brown California Aqueduct to agricultural users in the San Joaquin Valley and to urban users in Southern California. The South Bay Pumping Plant also lifts water from the Bethany Reservoir into the South Bay Aqueduct.[74]

The State Water Project is the largest consumer of electrical energy in the state, requiring an average of 5,000 GWh per year.[75] The energy required to operate the SWP is provided by a combination of DWR's own hydroelectric and other generation plants and power purchased from other utilities. The project's eight hydroelectric power plants, including three pumping-generating plants, and a coal-fired plant produce enough electricity in a normal year to supply about two-thirds of the project's necessary power.

Energy requirements would be considerably higher if the SWP was delivering full entitlement volumes of water. The project has in fact been delivering an average of approximately half its contracted volumes throughout the 1980s and 1990s.[76]

California State Water Project

The California Aqueduct moves water south along the west side of the San Joaquin Valley. It transports water to the Gianelli Pumping-Generating Plant and the San Luis Reservoir[77] which has a storage capacity of more than 2 million acre-feet.[78] SWP water not stored in San Luis Reservoir, and water released from San Luis, continues to flow south through the San Luis Canal, a portion of the California Aqueduct jointly owned by the Department and the USBR. As the water flows through the San Joaquin Valley, it is raised over 1,000 feet by four pumping plants—Dos Amigos, Buena Vista, Teerink, and Chrisman — before reaching the foot of the Tehachapi Mountains. In the San Joaquin Valley near Kettleman City, the Coastal Branch Aqueduct extends west to serve municipal and industrial water users in San Luis Obispo and Santa Barbara counties.

The remaining water conveyed by the California Aqueduct is delivered to Southern California. Pumps at Edmonston Pumping Plant, situated at the foot of the mountains, raise the water 1,926 feet — the highest single lift of any pumping plant in the world. Then the water enters 8.5 miles of tunnels and siphons as it flows into the Antelope Valley, where the California Aqueduct divides into two branches, the East Branch and the West Branch. The East Branch carries water through the Antelope Valley into Silverwood Lake in the San Bernardino Mountains. From Silverwood Lake, the water flows through the San Bernardino Tunnel into the Devil Canyon Powerplant. The water continues down the East Branch to Lake Perris, the southernmost SWP reservoir. Water in the West Branch flows through the Warne Powerplant into Pyramid Lake in Los Angeles County. From there it flows through the Angeles Tunnel and Castaic Powerplant into Castaic Lake, terminus of the West Branch.

California Department of Water Resources, 1996, *Management of the California State Water Project*. Bulletin 132-96.

Names and Locations of Primary State Water Delivery Facilities

Central Valley Project

The Central Valley Project (CVP) is a federal project operated by the U.S. Bureau of Reclamation. The Bureau is the largest wholesaler of water in the country, providing water to more than 31 million people. One out of five Western farmers (140,000) uses Bureau irrigation water for 10 million acres of farmland that produce 60% of the nation's vegetables and 25% of its fruits and nuts.[79]

The Bureau of Reclamation notes that the "fundamental equation of Western water today" is that "supply is finite" and that with growing demand, the west must "develop and maintain highly efficient water use practices" in order to "sustain its ecosystems" and provide for prosperity.[80]

The Central Valley Project is comprised of a number of elements. The major reservoirs are outlined below:

Major Central Valley Project Reservoirs[81]

Reservoir	*Capacity (taf)*	*Year Completed*	*Stream*
Shasta	4,552	1945	Sacramento River
Trinity	2,448	1962	Trinity River
New Melones	2,420	1979	Stanislaus River
Folsom	977	1956	American River
San Luis (Federal Share)	966	1967	Offstream
Millerton	520	1947	San Joaquin River
Whiskeytown	241	1963	Clear Creek

The largest facility is on the Sacramento River, which flows from the northern end of the Central Valley south to the delta.

Sacramento River, showing normal processes of depositing soils and changing course.

Colorado River Aqueduct

Significant volumes of water are imported to the Los Angeles Basin and San Diego in Southern California from the Colorado River via the Colorado River Aqueduct (CRA). The aqueduct was built by the Metropolitan Water District of Southern California (MWD). Though MWD's allotment of the Colorado River water is 550,000 afy, it has historically extracted as much as 1.3 mafy through a combination of waste reduction arrangements with IID (adding about 106,000 afy) and by using "surplus" water.[82] The Colorado River water supplies require about 2,000 kWh/af for conveyance to the Los Angeles basin.

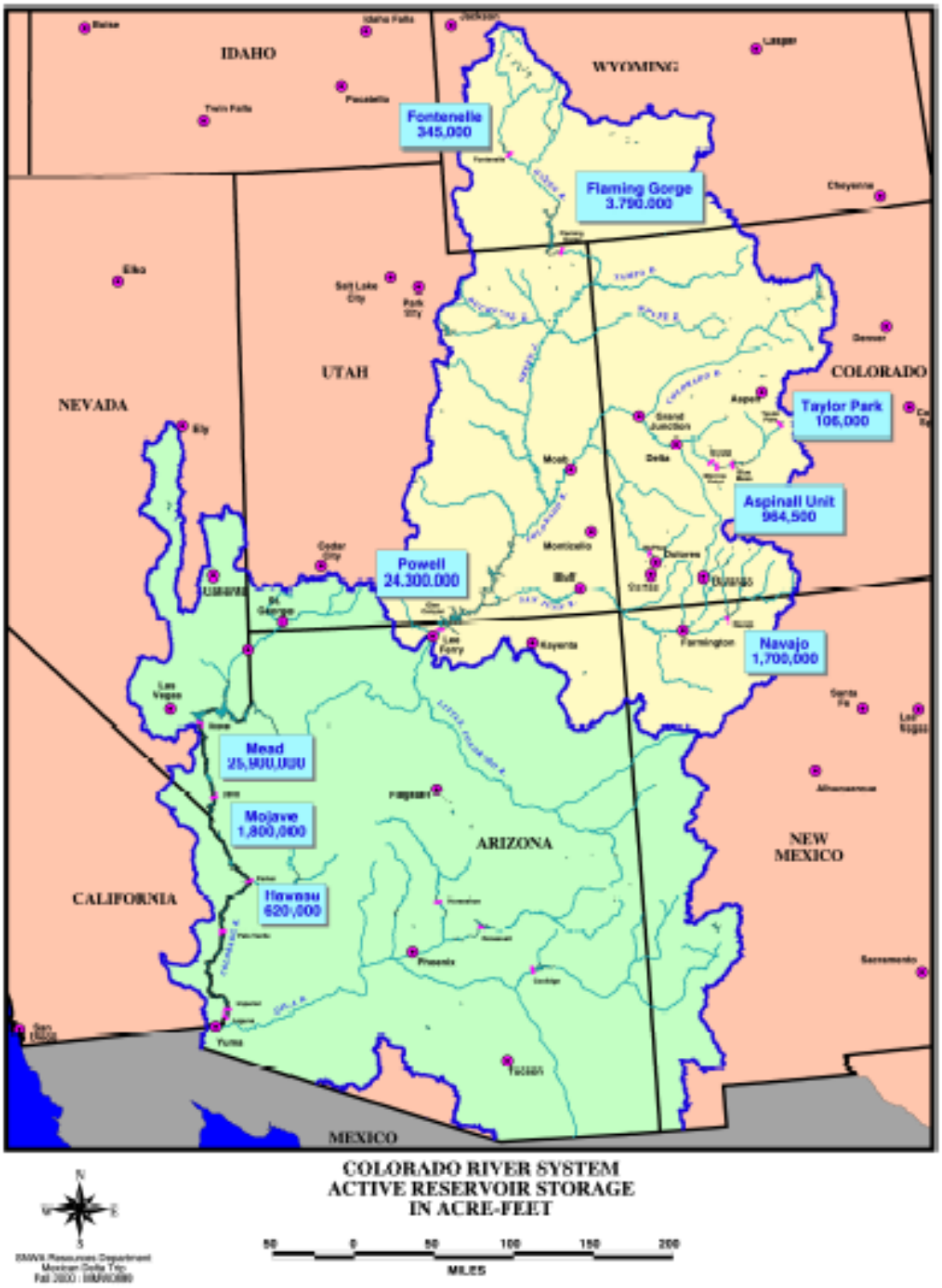
Source: Gerald R. Zimmerman, 2002. Executive Director, Colorado River Board of California, Presentation to DWR Bulletin 160-03 Advisory Committee.

The Colorado River watershed basin and flows are as follows:

Colorado River Watershed[83]

- About 250,000 square miles
- About 1,400 miles long
- Over 60 maf of storage
- Average annual unimpeded flow:
  15.1 maf at Lee Ferry
  16.5 maf at the NIB (Mexico-U.S. border)

Colorado River Watershed



Source: Gerald R. Zimmerman, 2002. Executive Director, Colorado River Board of California, Presentation to DWR Bulletin 160-03 Advisory Committee.

The Colorado River Aqueduct extends 242 miles from Lake Havasu on the Colorado River to its terminal reservoir, Lake Mathews, near Riverside. The Colorado River aqueduct was completed in 1941 and expanded in 1961 to a capacity of more than 1 MAF per year. Five pumping plants lift the water 1,616 feet, over several mountain ranges, to southern California. To pump an average of 1.2 million acre-feet of water per year into the Los Angeles basin requires approximately 2,400 GWh of energy for the CRA's five pumping plants.[84] On average, the energy required to import Colorado River water is about 2,000 kWh/AF. The aqueduct was designed to carry a flow of 1,605 cfs (with the capacity for an additional 15%).

Source: Gerald R. Zimmerman, 2002. Executive Director, Colorado River Board of California, Presentation to DWR Bulletin 160-03 Advisory Committee.

The sequence for pumping the water supplies is as follows: The Whitsett Pumping Plant elevates water from Lake Havasu 291 feet out of the Colorado River basin. At "mile 2," Gene pumping plant elevates water 303 feet to Iron Mountain pumping plant at mile 69, which then boosts the water another 144 feet. The last two pumping plants provide the highest lifts - Eagle Mountain, at mile 110, lifts the water 438 feet, and Hinds Pumping Plant, located at mile 126, lifts the water 441 feet.[85]

MWD has recently improved the system's energy efficiency. The average energy requirement for the CRA was reduced from approximately 2,100 kWh /af to about 2,000 kWh /af "through the increase in unit efficiencies provided through an energy efficiency program."[86] The energy required to pump each af of water through the CRA is essentially constant, regardless of the total annual volume of water pumped. This is due to the 8-pump design at each pumping plant. The average pumping energy efficiency does not vary with the number of pumps operated, and the

same 2,000 kWh /af estimate is appropriate for both the "Maximum Delivery Case" and the "Minimum Delivery Case."[87]

Based on the relatively steep grade of the CRA, limited active water storage, and transit times between plants, the system does not generally lend itself to shifting pumping loads from on-peak to off-peak. Under the Minimum Delivery Case, the reduced annual water deliveries would not necessarily bring a reduction in annual peak load, since an 8-pump flow may still need to be maintained in certain months.[88]

Electricity to run the CRA pumps is provided by power from hydroelectric projects on the Colorado River as well as off-peak power purchased from a number of utilities. The Metropolitan Water District has contractual hydroelectric rights on the Colorado River to "more than 20 percent of the firm energy and contingent capacity of the Hoover power plant and 50 percent of the energy and capacity of the Parker power plant."[89] Energy purchased from utilities makes up approximately 25 percent of the remaining energy needed to power the Colorado River Aqueduct.[90]

The Metropolitan Water District

The Metropolitan Water District of Southern California (MWD) is a regional water wholesaler that imports water from the Colorado River and Northern California for resale to agencies in Southern California. Because MWD is the principal water supplier for southern California and an important link in the state's two most energy-intensive interbasin water transfers, the SWP and the CRA, it is described in some detail in this section.

Member Agencies of the MWD of Southern California

City of Anaheim	Three Valleys MWD
Foothill MWD	Inland Empire Utilities Agency
City of San Fernando	City of Los Angeles
City of Beverly Hills	City of Torrance
City of Fullerton	City of Long Beach
City of San Marino	MWD of Orange County
City of Burbank	Upper San Gabriel Valley MWD
City of Glendale	City of Compton
City of Santa Ana	City of Pasadena
Calleguas MWD	West Basin MWD
Las Virgenes MWD	Eastern Municipal Water District
City of Santa Monica	San Diego County Water Authority
Central Basin MWD	Western MWD of Riverside County

The Colorado River is one of the primary sources of water supply for MWD. MWD is also the largest user of SWP supplies. Even with both these major imported supply sources, *local* water still provides the largest share of supplies – and it is growing – in MWD's service area.

Sources of Water for the South Coast (1985-1999)[91]

- Colorado River (about 30 percent)
- State Water Project(about 20 percent)
- Los Angeles Aqueducts (about 10 percent)
- Local sources (about 40 percent)

MWD provides about 60 percent of the water used in portions of Los Angeles, Ventura, Orange, Riverside, San Bernardino, and San Diego counties.[92] The area served covers about 5,200 square miles.

MWD owns and operates transmission infrastructure and has long-term entitlements to the Hoover power plant and perpetual rights to the Parker power plant which provide sufficient power for the CRA. Metropolitan pays "approximately 70 percent of the total SWP power and transmission costs" arising from DWR's long-term agreements, and it Metropolitan owns generates hydroelectric power along Metropolitan's water distribution system.[93]

Metropolitan's Integrated Resources Plan identified the following water supply sources as "developable" to meet southern California's water uses: Colorado River Aqueduct, State Water Project, recycling wastewater, recovering groundwater, conservation, desalination, storage and water transfers and exchanges.[94]

Local Water Sources in Southern California

Nearly half (46%) of the water used in MWD's service area is in fact secured from *local* sources, and the percentage of total supplies provided by local sources is growing steadily.[95] This figure is up from approximately one-third provided by local surface and groundwater resources in the mid-1990s.[96] Metropolitan encourages local supply development through subsidies for recycling, groundwater recovery, conservation, and groundwater storage. In some parts of southern California, all water is provided by local supplies. In others, imported water from the Colorado River and/or the SWP make up all of the supply. In most areas in southern California, water supplied to users is a variable mix of SWP, CRA, and local supplies depending on the time of year, the hydrologic conditions in the particular year (e.g. wet conditions in the northern part of the state vs. local conditions). Local supplies are considerably less energy-intensive than CRA and SWP imported supplies due to the pumping requirements for importing both Colorado River and State water over mountain ranges.[97]

Elements of Urban Water Supply Systems

The major water extraction and conveyance systems, and local water sources, are the first element of the water supply system. Once water is provided to a specific location, it is treated and distributed to users, used for various purposes, collected in wastewater systems (except the portion that is "consumed" in processes), treated, and either re-used or discharged.

Treatment and Distribution

Once water is extracted from surface and/or groundwater sources and delivered to a geographic area where it is to be used, it is processed through treatment and/or filtration systems to meet health and other water quality standards. It is then delivered to end-users through local distribution systems.

Treatment processes and the system distribution and pressurization require varying amounts of energy depending on factors such as water quality, the topography of the area served, and system requirements. Treatment requirements, and therefore energy inputs, are increasing.[98] The technologies required for treatment are also increasingly expensive and are an important factor in water management. As Franklin Burton notes:[99]

> Recently promulgated regulations will have a significant impact on energy consumption in water treatment because many water utilities will install energy-consuming technologies such as ozone for disinfection and membrane filtration for the removal of particulate and organic matter. New filtration facilities will also be required to be added to existing surface supplies that currently are not treated (other than disinfection). Existing facilities will also be upgraded if they do not meet new requirements for disinfection.

Treatment is designed to deal with contaminants and disinfection or treatment by-products such as the following:

- trihalomethanes (TTHMs)
- haloacetic acids (HAAs)
- chlorinated organic compounds that are suspected carcinogens
- bacteria
- Giardia lamblia
- Cryptosporidium

Conventional surface water treatment technologies commonly use physical methods such as sedimentation and filtration to remove suspended material from the water and chemical disinfection – mostly with chlorine – to control bacteria, viruses, and *Giardia lamblia*. Chemical processes may be added such as coagulation to enhance the effectiveness of sedimentation and

chemical softening to remove the dissolved salts responsible for hardness. After treatment, water is usually pumped at high pressure to the distribution and storage system.

Wastewater Catchment and Treatment

Most M&I water users are connected to wastewater systems which collect and treat it to prescribed standards.[100] (Some areas utilize septic systems.) Increasingly, water is being re-used following treatment. Otherwise treated water is returned to natural water courses or to the sea. Wastewater systems require energy for pumping in the collection systems and for pumping, treatment operations and processes, and solids processing in the treatment facilities.[101] New treatment processes such as UV also use energy.[102] The treatment processes is described in *Water and Wastewater Industries: Characteristics and Energy Management Opportunities* as follows:

> Wastewater treatment requires a combination of physical operations (such as pumping, screening, settling, and filtration) and chemical and biological processes for the removal of pollutants. In biological processes, cultures of microorganisms are used to clean the water by removing suspended and dissolved organic pollutants. The most common form of biological treatment used in wastewater treatment is activated sludge. Activated sludge requires aeration, either by mechanical aerators or blower-operated diffused air, to supply oxygen to the microorganisms. Wastewater aeration, pumping and solids processing account for most of the electric energy used in wastewater treatment.[103]

Wastewater catchment systems are generally designed to operate with gravity flow. In many instances, however, pumping is required to move wastewater to the treatment facility.[104]

Potential Impacts of Climate Change on Water Systems in California

All of the elements California's water system described above, from reservoirs and conveyance systems to wastewater treatment systems, will be impacted by climate change and variability. In some cases, change may be beneficial. In others it may pose difficult challenges. This section reviews what is known regarding potential impacts of climate change on these critical water systems.

The Water Sector Report summarized the team's findings as follows:

Key findings of the National Water Sector Assessment[105]

In many cases and in many locations, there is compelling scientific evidence that climate changes will pose serious challenges to our water systems.

It is vital that uncertainties not be used to delay or avoid taking certain kinds of action now. Water managers and policymakers must start considering climate change as a factor in all decisions about water investments and the operation of existing facilities and systems.

A continued reliance solely on current engineering practice may lead us to make incorrect – and potentially dangerous or expensive – decisions.

The following is a synthesis of the major findings of the water sector assessment report that are directly applicable to the California region:

The Nature of Expected Climate Changes[106]

- Average surface temperatures will continue to increase. (very high confidence)
- Regional and seasonal pattern of temperature increases across the U.S. will vary. (very high confidence)
- Global average precipitation will increase. (very high confidence)
- There will be changes in the timing and regional patterns of precipitation. (very high confidence)
- Temperature increases in mountainous areas with seasonal snowpack will lead to increases in the ratio of rain to snow and decreases in the length of the snow storage season. (very high confidence) It is likely that reductions in snowfall and earlier snowmelt and runoff would increase the probability of flooding early in the year and reduce the runoff of water during late spring and summer. Basins in the western United States are particularly vulnerable to such shifts.
- Average precipitation will increase in higher latitudes, particularly in winter (high confidence).
- Increases in annual average runoff in the high latitudes caused by higher precipitation are likely to occur (high confidence). Research results suggest that flood frequencies in some areas are likely to change. In northern latitudes and snowmelt-driven basins, research results suggest with medium confidence that flood frequencies will increase, although the amount of increase for any given climate scenario is uncertain and impacts will vary among basins.
- Research results suggest that drought frequencies in some areas are likely to change.[107]
- Higher sea levels associated with thermal expansion of the oceans and increased melting of glaciers will push salt water further inland in rivers, deltas, and coastal aquifers (very high confidence). It is well understood that such advances would adversely affect the quality and quantity of freshwater supplies in many coastal areas.
- Water-quality problems will worsen where rising temperatures are the predominant climate change (high confidence). Where there are changes in flow, complex positive and negative changes in water quality will occur. Specific regional projections are not well-established at this time because of uncertainties in how regional flows will change.
- Increased atmospheric carbon dioxide will affect the use of water by vegetation (high confidence), but hydrologists have low confidence in the net effects of this and other competing influences.[108]

Significant issues relating to water systems need to be addressed by decision-makers, water managers, and society. As the Water Sector Study notes: "The current state-of-the-science suggests that plausible climate changes, projected by general circulation models, raise a wide range of concerns that should be addressed by national and local water managers and planners, climatologists, hydrologists, policymakers, and the public."[109]

Major Impacts of Climate Variability and Change on U.S. Water Resources[110]

- In spite of many remaining uncertainties, model results suggest that some significant changes in the timing and amount of runoff will result from plausible changes in climatic variables (high confidence).
- With few exceptions, we have low confidence that we can determine specific changes for specific regions. In the arid and semi-arid western United States, it is well established that relatively modest changes in precipitation can have proportionally large impacts on runoff.
- Research indicates that U.S. watersheds with a substantial snowpack in winter will experience major changes in the timing and intensity of runoff as average temperatures rise (very high confidence). Reductions in spring and summer runoff, increases in winter runoff, and earlier peak runoff are all common responses to rising temperatures.
- Research to date suggests that there is a risk of increased flooding in parts of the U.S. that experience large increases in precipitation (medium confidence).
- Non-linear or threshold events are likely to occur, but are difficult to project. (Examples include a fall in lake level that cuts off outflows or separates a lake into two separate parts, an increase in flood intensity that passes specific damage thresholds, and exceedance of water-quality limits.)
- Relative sea-level rise adversely affects groundwater aquifers and freshwater coastal ecosystems (high confidence). Rising sea level causes an increase in the intrusion of salt water into coastal aquifers. Other impacts of sea-level rise are likely to include changes in salinity distribution in estuaries, altered coastal circulation patterns, destruction of transportation infrastructure in low-lying areas, and increased pressure on coastal levee systems.
- Climate changes have the potential to alter water quality significantly by changing temperatures, flows, runoff rates and timing, and the ability of watersheds to assimilate wastes and pollutants.

Climate Trends in California

This analysis of potential impacts to California's water systems begins with a review of key trends over the past century in temperature, precipitation, and runoff.

Temperature Trends in California

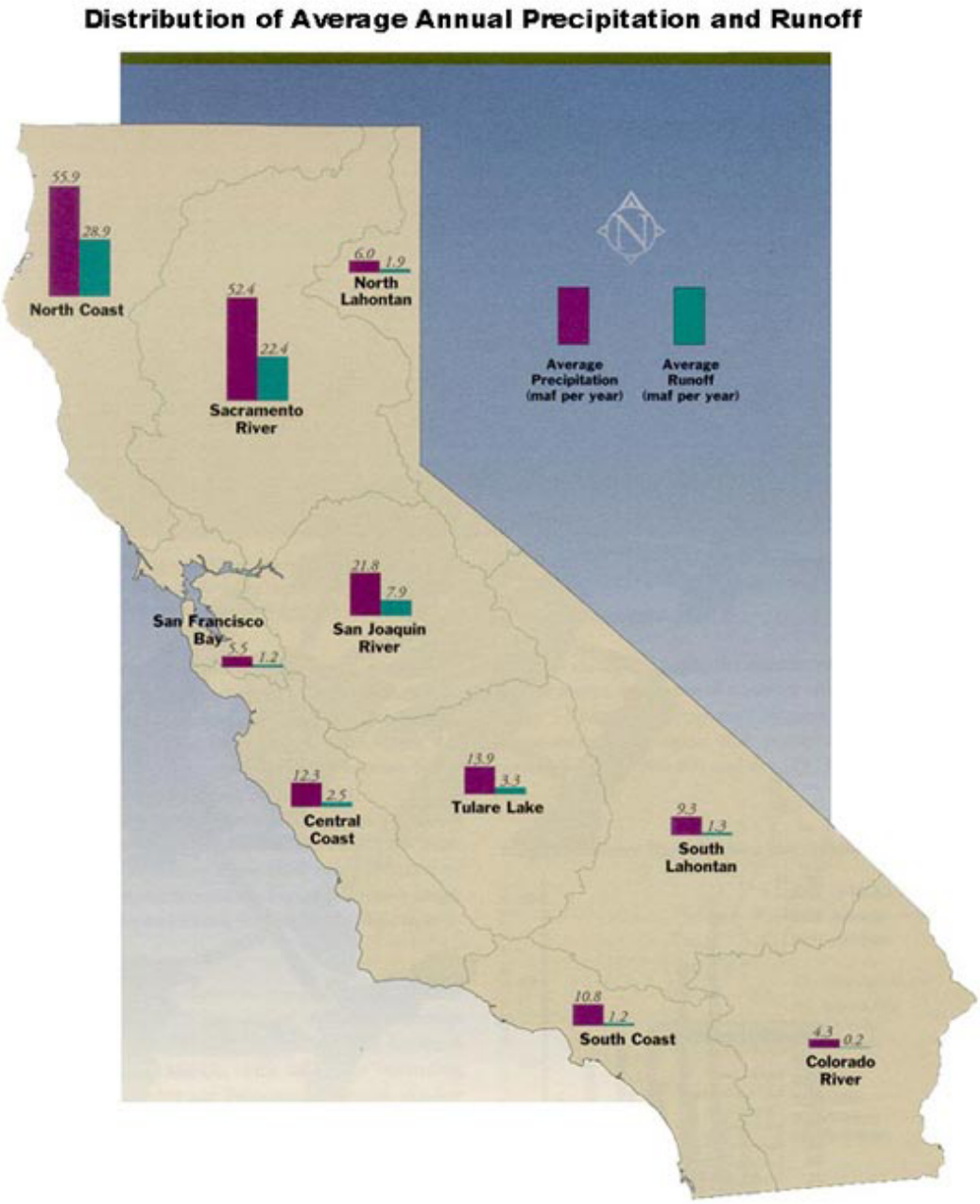
Winter temperatures in the Sierra Nevada rose by almost 4°F (2°C) during the second half of the 20th century, and a trend toward earlier snowmelt and outflow to the San Francisco–San Joaquin Delta over the same period was detected by Dettinger and Cayan.[111] Water managers are particularly concerned with the mid-range elevation levels where snow shifts to rain under

warmer conditions, thereby changing the snow storage. Research is indicating earlier melting and flows, as described in more detail below.

Roos notes that "California inland rural temperatures do not seem to have followed the world trend and have risen only slightly since 1940.[112] California coastal temperatures, even in rural locations, do show warming in the 1980s and 1990s corresponding to warmer ocean temperatures."[113]

Precipitation Trends in California

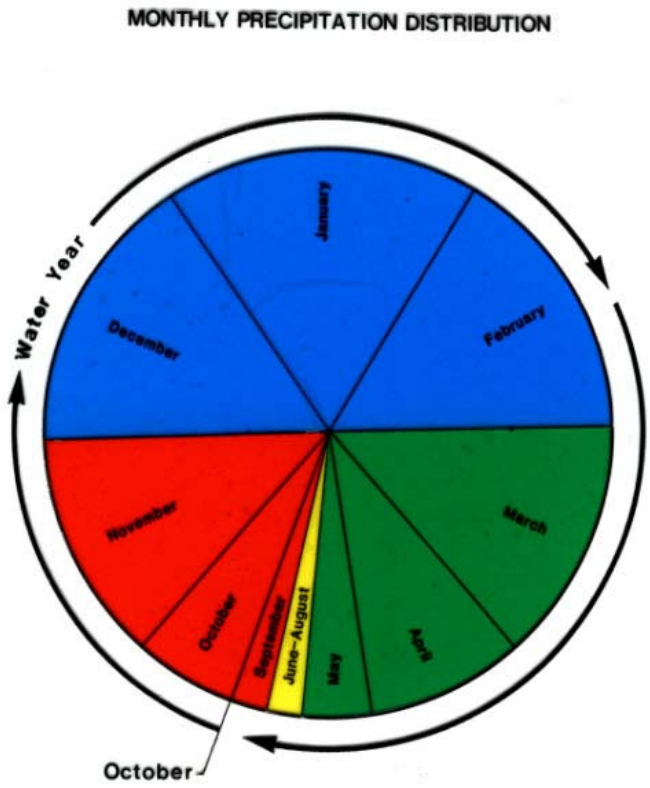
California's precipitation trends follow a Mediterranean pattern of wet winters and dry summers.



Source, Department of Water Resources

For *global average conditions*, the water sector report notes that; "There is a very high degree of confidence among climatologists and modelers that global climate change will, on average, result in a wetter world. Climate models consistently project an increase in global mean precipitation of between three and 15% for a temperature increase of 1.5 to 3.5º C."[114] California's precipitation patterns vary in different parts of the region. Roos concludes that "General circulation models poorly reproduce detailed precipitation patterns. Precipitation relies on meteorological conditions that often occur at scales smaller than GCMs currently resolve. As a result, accurate regional precipitation projections require GCM models with higher resolution and accuracy than current models provide."[115]

Roos notes that "Northern and Central California precipitation is quite seasonal, a Mediterranean climate, with cool wet winters and warm dry summers. On average, half the annual precipitation occurs in the three months of December, January, and February. Three-fourths occurs in the five month November through March period. The only significant departures are in the dry southeastern desert areas, which have a summer monsoon peak as well as a winter season maximum."[116]



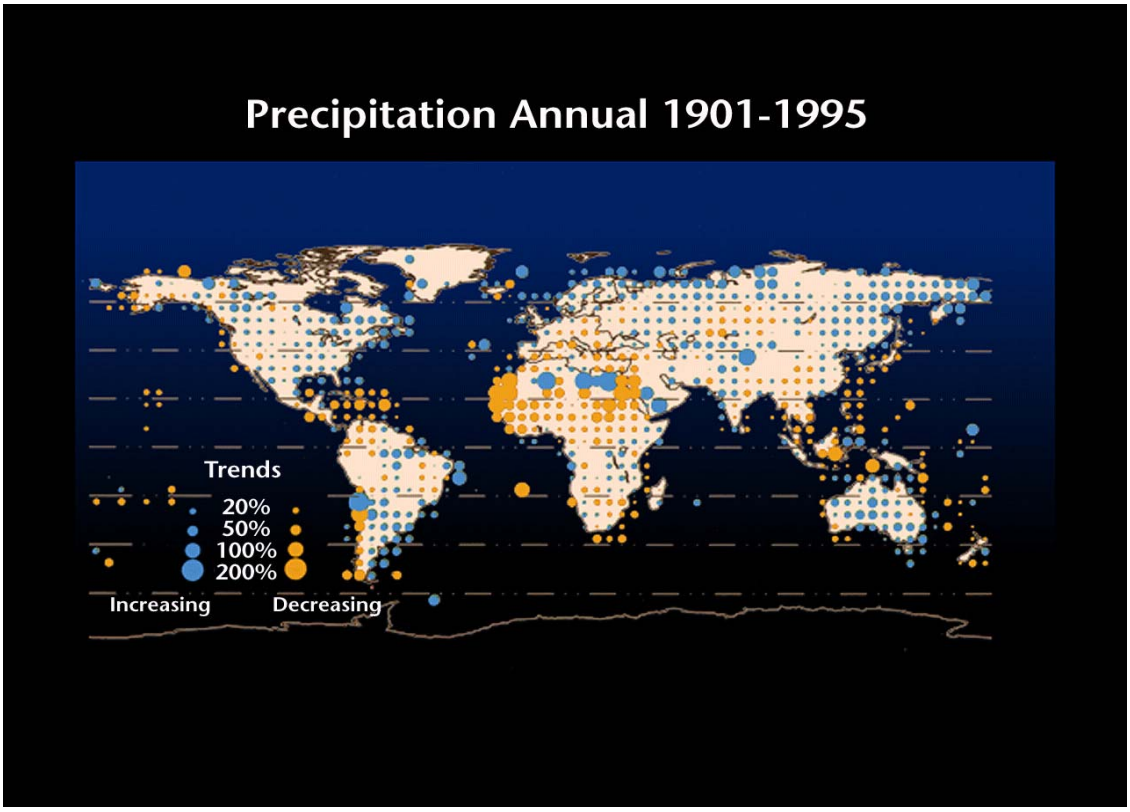
Monthly Precipitation Distribution in the Sierra Nevada
Source: Maurice Roos, based on 1947-86 precipitation records for Sierra stations as compiled by DWR & Scripps.

Precipitation Trends in the United States[117]

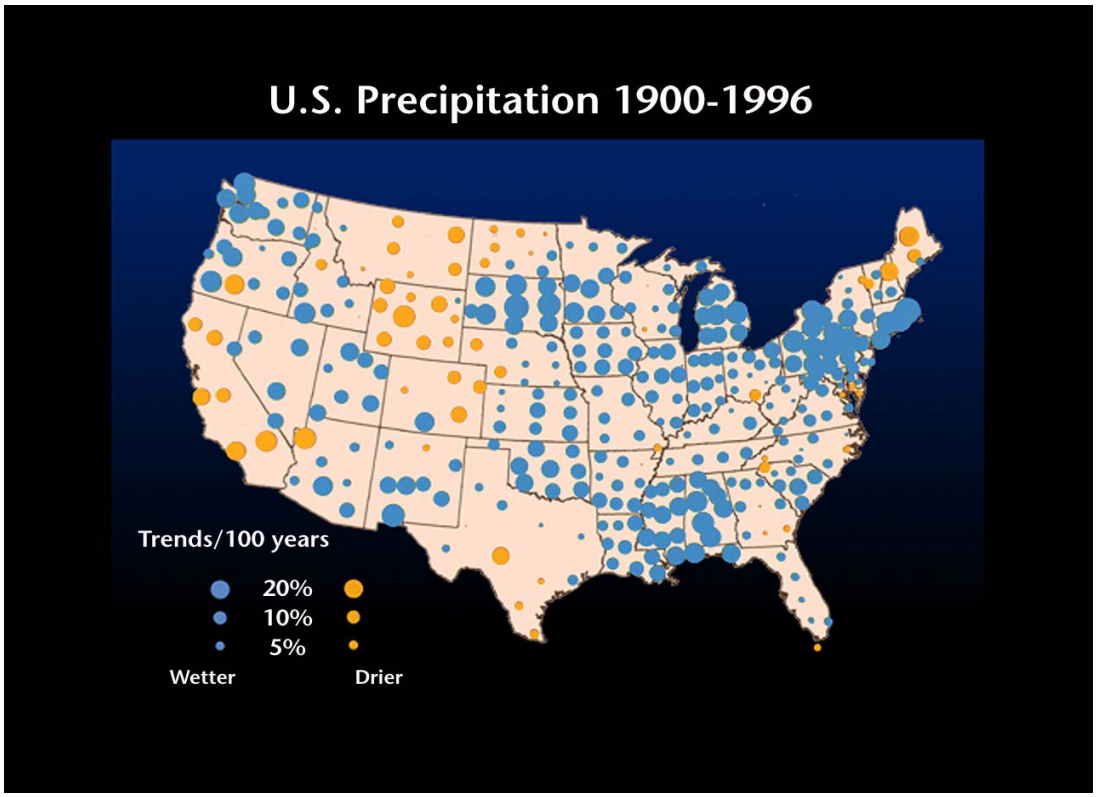
Karl and Knight[118] show an increase in precipitation in the continental United States, with most of the increase in the highest annual one-day precipitation event – a potentially worrisome trend in regions where flooding is a problem. By analyzing long-term precipitation trends in the United States, they determined that:

- Precipitation over the contiguous United States has increased by about 10% since 1910;

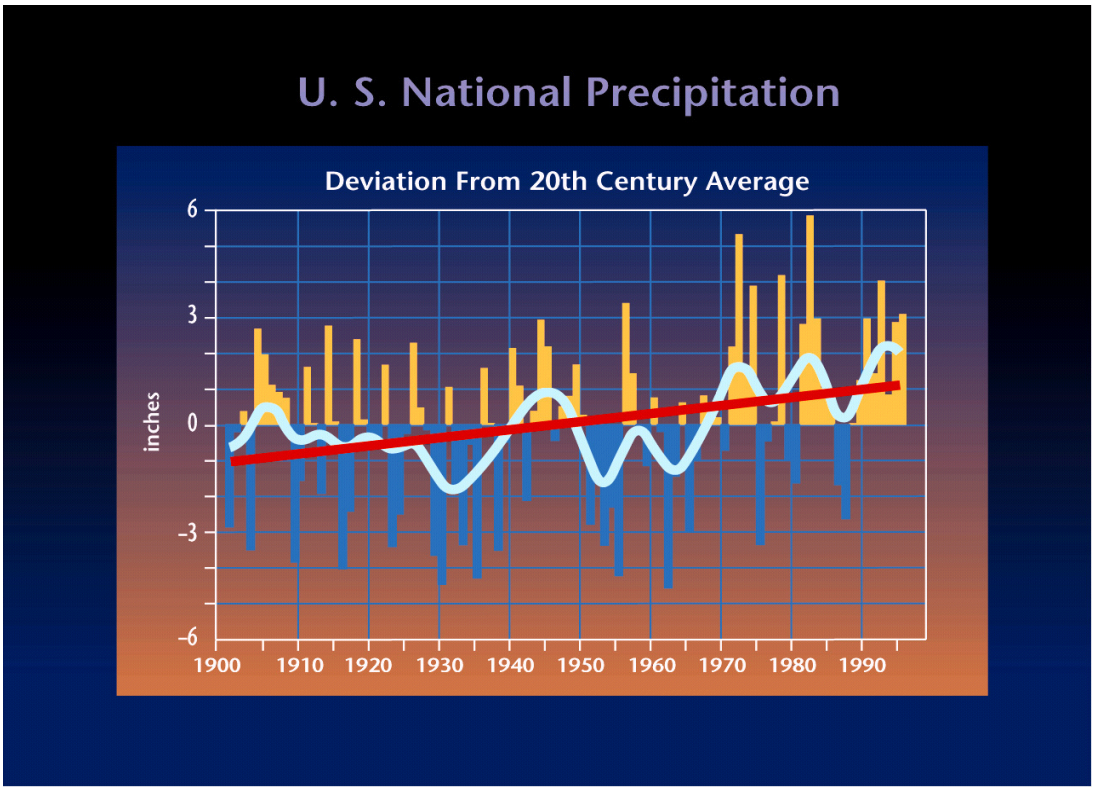
- The intensity of precipitation has only increased for very heavy and extreme precipitation days;
- Increases in total precipitation are strongly affected by increases in both the frequency and the intensity of heavy and extreme events, measured as the highest 1-day annual precipitation event;
- The probability of precipitation on any given day has increased;
- The proportion of total precipitation from heavy events has increased at the expense of moderate precipitation events.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Runoff Trends in California

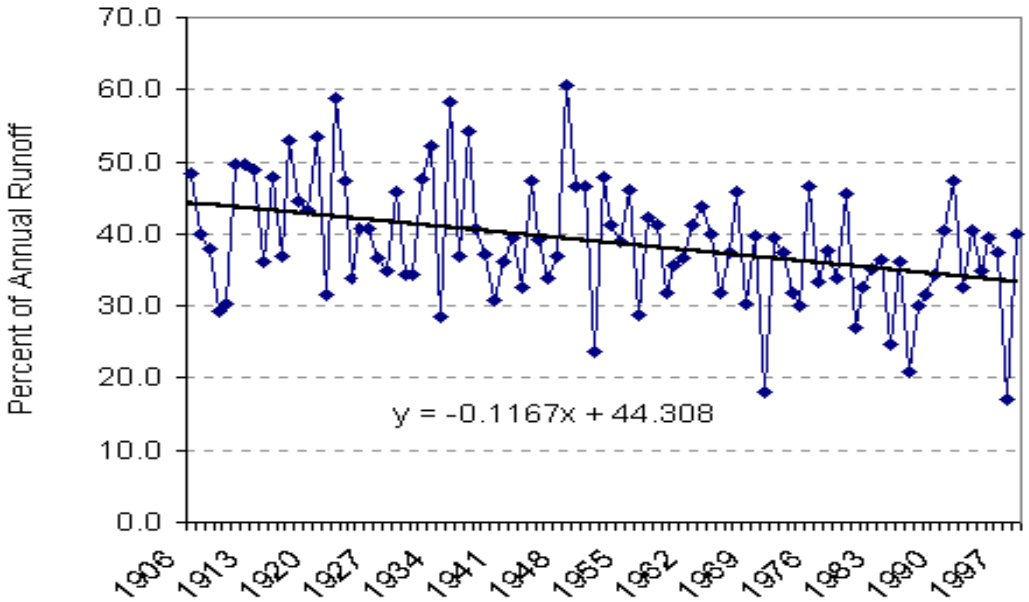
California runoff indexes for both the Sacramento and San Joaquin Rivers show a marked decline in flows during the critical April to July period over the past century. Dettinger and Cayan found that for the second half of the 1900s (1948 and 1991) snowmelt-generated runoff came increasingly early in the water year in many basins in northern and central California.[119] A declining fraction of the annual runoff was occurring during the months of April to June in middle-elevation basins, while an increasing fraction was occurring earlier in the water year, particularly in March.[120] Wilby and Dettinger made similar findings of increasing winter and spring floods under conditions in which rain falls on snow.[121]

Unimpaired Runoff[122]

"Unimpaired Runoff" or "Full Natural Flow" represents the natural water production of a river basin, unaltered by upstream diversions, storage, or by export or import of water to or from other watersheds. Gauged flows at the given measurement points are increased or decreased to account for these upstream operations. The result is the ``full natural flow," expressed as a rate (in Cubic Feet Per Second [CFS]), or as a volume over a fixed time interval, Acre-Feet (AF). Generally, “thousands of Acre-Feet” (TAF) is used. Our convention is to use “TAF” rather than “KAF,” which would designate kilo-acre-feet.

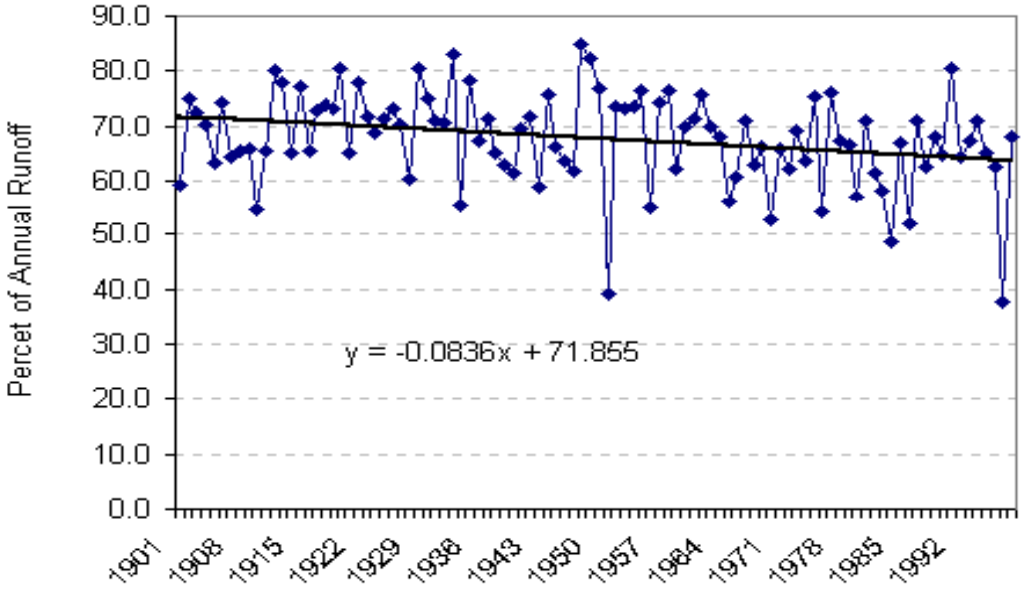
An earlier analysis by Gleick examined the potential for shifts in runoff in California due to increased temperature.[123] Gleick used a water-balance model developed for the Sacramento Basin. Climate change scenarios were based on increases in average monthly temperature of 4º and 7°F (2º and 4°C) and changes in precipitation of +/- 10 and 20%. The study found that summer runoff decreased in all scenarios, whereas winter runoff rose in all those scenarios in which precipitation was kept constant or increased. With an increase in temperature of 7°F (4°C) and an increase in precipitation of 20%, the winter runoff rose by 75%, and the summer runoff decreased by 49%.

Sacramento River Index
April to July Runoff
(as Percent of Annual Runoff)



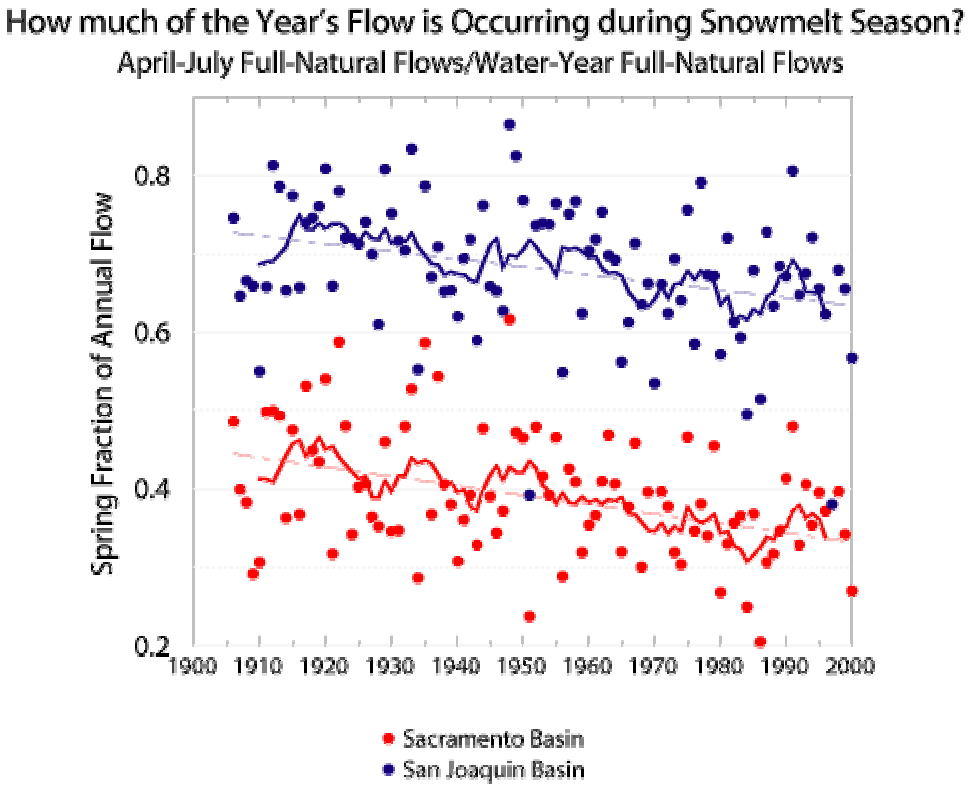
Dettinger, M.D. and D.R. Cayan, 1995. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. J. Climate, 8, 606-623. and Roos, M., 1991. A trend of decreasing snowmelt runoff in northern California. Proceedings, 59th Western Snow Conference, Juneau, AK, 29-36.

San Joaquin River Index
April to July Runoff
(as Percent of Annual Runoff)



Dettinger, M.D. and D.R. Cayan, 1995. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. J. Climate, 8, 606-623. and Roos, M., 1991. A trend of decreasing snowmelt runoff in northern California. Proceedings, 59th Western Snow Conference, Juneau, AK, 29-36.

A more recent plot of runoff data by Cayan appears to extend the trend:



Source: Dan Cayan, Scripps/USGS, CALFED Science Conference

A plot of the same river systems is provided by the following graphs from DWR. Note the increase in variability in the latter half of the time period.

Source: California Department of Water Resources, http://watersupplyconditions.water.ca.gov/hydrowatersupply.htm

Drought Trends in California

California has experienced major drought events in the 20th century. Over longer time scales, there is evidence of droughts that far exceed those in the recorded historical record.[124] In discussing drought events, it is useful to clarify how droughts are defined. NOAA provides the following useful distinctions:

What is a drought?[125]

A drought is a period of abnormally dry weather which persists long enough to produce a serious hydrologic imbalance (for example crop damage, water supply shortage, etc.) The severity of the drought depends upon the degree of moisture deficiency, the duration and the size of the affected area.

There are four different ways that drought can be defined:

Meteorological - a measure of departure of precipitation from normal. Due to climatic differences what is considered a drought in one location may not be a drought in another location.

Agricultural - refers to a situation when the amount of moisture in the soil no longer meets the needs of a particular crop.

Hydrological - occurs when surface and subsurface water supplies are below normal.

Socioeconomic- refers to the situation that occurs when physical water shortage begins to affect people.

The California Department of Water Resources characterizes drought as follows:[126]

> Drought is a gradual phenomenon. Although droughts are sometimes characterized as emergencies, they differ from typical emergency events. Most natural disasters, such as floods or forest fires, occur relatively rapidly and afford little time for preparing for disaster response. Droughts occur slowly, over a multiyear period. There is no universal definition of when a drought begins or ends. Impacts of drought are typically felt first by those most reliant on annual rainfall -- ranchers engaged in dryland grazing, rural residents relying on wells in low-yield rock formations, or small water systems lacking a reliable source. Criteria used to identify statewide drought conditions do not address these localized impacts. Drought impacts increase with the length of a drought, as carry-over supplies in reservoirs are depleted and water levels in groundwater basins decline.

The driest single year of California's measured hydrologic record was 1977. California's most recent multi-year drought was 1987-92.

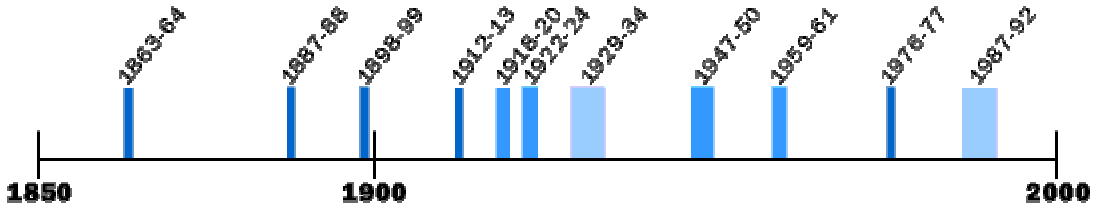
Droughts exceeding three years have been relatively rare in Northern California in the recent past. DWR notes that the 1929-34 drought established the criteria commonly used in designing storage capacity and yield of large Northern California reservoirs. The table below compares the 1929-34 drought in the Sacramento and San Joaquin Valleys to the 1976-77 and 1987-92 droughts.

Severity of Extreme Droughts in the Sacramento and San Joaquin Valleys

Drought Period	Sacramento Valley Runoff (maf/yr)	(% Average 1901-96)	San Joaquin Valley Runoff (maf/yr)	(% Average 1906-96)
1929-34	9.8	55	3.3	57
1976-77	6.6	37	1.5	26
1987-92	10.0	56	2.8	47

DWR notes that "Measured hydrologic data for droughts prior to 1900 are minimal. Multi-year dry periods in the second half of the 19th century can be qualitatively identified from the limited records available combined with historical accounts, as illustrated in the figure below, but the severity of the dry periods cannot be directly quantified."[127]

California's Multi-Year Historical Dry Periods
1850-present



Source: California Department of Water Resources, http://watersupplyconditions.water.ca.gov/background.htm

Drought affects California in a number of ways. Agricultural and urban water users are impacted by reductions in supply deliveries, hydro-power generation is reduced, and ecosystems and species are stressed due to both reduced flows, generally higher water temperatures, and water quality. During the last prolonged drought in California (1987-1992) both the SWP and the CVP sharply reduced deliveries. In 1991, the Central Valley Project reduced agricultural water deliveries by 75 percent and urban deliveries by 25 percent. The State Water Project actually eliminated deliveries to agricultural users and reduced urban deliveries by 70 percent. The state

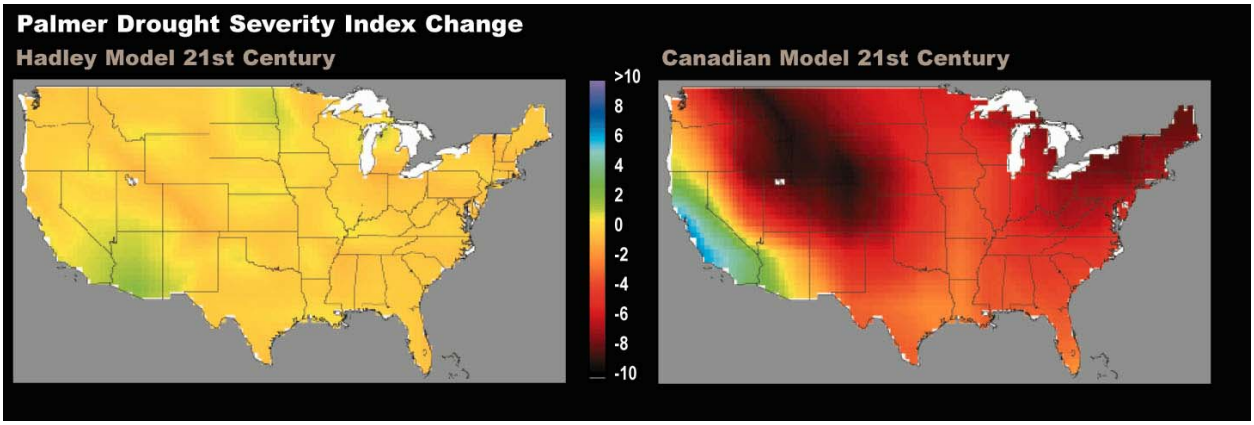
established a “drought water bank” to transfer water to those who had critical needs. Glick and Nash report that electricity costs increased by more than $3 billion due to reduced hydropower power production, and “recreation was adversely impacted. Visits to California state parks declined by 20%, and water-based activities such as skiing and reservoir fishing declined.”[128]

Accurate assessments of the full economic impacts of droughts are difficult to make. The water sector analysis notes that:

> Quantifying the socioeconomic impacts of a drought is difficult, and comprehensive damage estimates are rarely available. Agriculture, the economic sector most susceptible to water shortages, is likely to suffer reduced crop production, soil losses due to dust storms, and higher water costs during a drought. But non-climate factors can play an important role in limiting, or worsening, the impacts of climate. Agricultural losses during California’s six-year drought from 1987-1992 were reduced by temporarily fallowing some land, pumping more groundwater, concentrating water supplies on the most productive soils and higher value crops, and purchasing water in spot markets to prevent the loss of tree crops. Direct economic losses to California’s irrigated agriculture in 1991 were estimated at only $250 million, less than two percent of the state’s total agricultural revenues.[129]
>
> These kinds of impacts can be evaluated, and explicit costs can sometimes be assigned to them. However, not all of the impacts of drought are so readily quantified. During the 1987-1992 California drought, the state’s environmental resources may have suffered the most severe impacts. Most major fisheries suffered sharp declines and many trees were weakened or killed by the lack of precipitation, increasing the subsequent risk of forest fires.[130] These kinds of ecosystem impacts are rarely monetized or quantified.

Reduced freshwater flows in the Sacramento–San Joaquin Delta due to drought conditions increases salinity at key locations.[131] During the 1987–1992 drought, reduced flows combined with water exports from the delta caused higher salinity levels and violations of water quality standards in 1990, 1991, and 1992.[132]

The Palmer Drought Severity Index analysis using the two GCMs for the national assessment indicate an interesting anomaly for the west coast. As the maps below indicate, severe drought in other parts of the country is at variance from the California coastal conditions in the Canadian run, and the Hadley run indicates slightly wetter conditions in the southwest.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

The Palmer Drought Severity Index[133]

The Palmer Index was developed by Wayne Palmer in the 1960s and uses temperature and rainfall information in a formula to determine dryness. It has become the semi-official drought index.

The Palmer Index is most effective in determining long term drought—a matter of several months—and is not as good with short-term forecasts (a matter of weeks). It uses a 0 as normal, and drought is shown in terms of minus numbers; for example, minus 2 is moderate drought, minus 3 is severe drought, and minus 4 is extreme drought. At present, northern Virginia is at a minus 4.0 point; north central Maryland is at a minus 4.2 level, and southern Maryland is at least a minus 4 level.

The Palmer Index can also reflect excess rain using a corresponding level reflected by plus figures; i.e., 0 is normal, plus 2 is moderate rainfall, etc. At present, north central Iowa is at a plus 5.2 level, and parts of South Dakota are even higher.

The advantage of the Palmer Index is that it is standardized to local climate, so it can be applied to any part of the country to demonstrate relative drought or rainfall conditions. The negative is that it is not as good for short term forecasts, and is not particularly useful in calculating supplies of water locked up in snow, so it works best east of the Continental Divide.

The Crop Moisture Index (CMI) is also a formula that was also developed by Wayne Palmer subsequent to his development of the Palmer Drought Index.

The CMI responds more rapidly than the Palmer Index and can change considerably from week to week, so it is more effective in calculating short-term abnormal dryness or wetness affecting agriculture.
CMI is designed to indicate normal conditions at the beginning and end of the growing season; it uses the same levels as the Palmer Drought Index.

It differs from the Palmer Index in that the formula places less weight on the data from previous weeks and more weight on the recent week.

Based on long-term analysis of climate change and variability, the droughts of the 1900s may in fact be mild.

The Paleoclimate Record

Paleoclimatology is the study of climate prior to the instrumental record. Using information from ice cores, tree rings, pollen, and other records as a "proxy" for direct measurements, scientists reconstruct climate records of the past. In California and the Southwest United States, trees are a valuable record. Trees provide important information about past climatic conditions through the width and density of annual growth rings and through isotopic composition.

The long-term climate record provided by paleoclimate techniques provides clues about patterns of drought in the region. The following record of droughts extends to approximately 11,000 years ago.

California Droughts in the Paleoclimate Record [134]

11,000 years before present	Beginning of Holocene Epoch- Recent time, the time since the end of the last major glacial epoch
6,000 years before present	Approximate time when trees were growing in areas now submerged by Lake Tahoe. Lake levels were lower then, suggesting a drier climate.
900-1300 A.D.(approximate)	The Medieval Warm Period, a time of warmer global average temperatures. The Arctic ice pack receded, allowing Norse settlement of Greenland and Iceland. The Anasazi civilization in the Southwest flourished, its irrigation systems supported by monsoonal rains.
1300-1800 A.D. (approximate)	The Little Ice Age, a time of colder average temperatures. Norse colonies in Greenland failed near the start of the time period, as conditions became too cold to support agriculture and livestock grazing. The Anasazi culture began to decline about 1300 and had vanished by 1600, attributed in part to drought conditions that made agriculture infeasible.
Mid - 1500s A.D.	Severe, sustained drought throughout much of the continental U.S., according to dendrochronology. Drought suggested as a contributing factor in the failure of European colonies at Parris Island, South Carolina and Roanoke Island, North Carolina.
1850s A.D.	Sporadic measurements of California precipitation began.
1890s A.D.	Long-term streamflow measurements began at a few California locations

The Southwest Regional Assessment references paleoclimate work that is relevant to California as well:

> [135]In the Southwest, tree-ring based records have proven to be the most abundant and widely studied source of prerecorded climate history for the region. In select tree species, a new tree ring forms every year just in-side the bark of the tree's stem. These annual growth rings can be seen and compared to one another when nondestructive cores are taken from living trees. Stresses on the tree (such as lack of water or unusually hot temperatures) change various aspects of ring width and density in a given growing season. This creates a visible pattern within the core. This ring pattern can then be viewed against patterns from other older trees and dead tree remnants, thus extending back in time records of temperature and precipitation. In the Southwest, thicker rings indicate higher rainfall and above average moisture availability for the tree to utilize during its growing season.

The paleoclimate record is useful in increasing our understanding of long-term climate change, but it is sometimes difficult to interpret. MWD makes the following points regarding limitations of tree ring analysis:[136]

> Tree ring reconstructions are not without problems. Tree ring widths are related to moisture availability at the site in which the trees are growing and are not spatially integrated measures of conditions over a whole river basin. Tree ring widths are more sensitive to lack of precipitation which limits growth than they are to abundant precipitation during which time factors other than water may limit growth. This may impose a bias towards sensitivity to dry conditions in tree ring data. Precipitation that does not impact tree growth for whatever reason, will not be reflected in the tree ring record. This may include precipitation not on sampled forest areas, or that does not infiltrate, or that occurs outside the growing season.

Modeling Climate Change and Water

Norm Miller provides a good summary of modeling work in California relating to water and climate change (full references for this summary are provided in the footnote):[137]

> There have been a number of investigations of California hydrologic response focused on changes in streamflow volumes due to climate change (e.g. Revelle and Waggoner 1983, Gleick 1987, Lettenmaier and Gan 1990, Jeton et al. 1996, Miller et al. 1999, Wilby and Dettinger 2000, Knowles and Cayan 2001). Revelle and Waggoner (1983) developed regression models to estimate the sensitivity of streamflow in major basins to climate change from historical data. Gleick (1987) used a modified upper and lower basin water budget model (Thornwaite 1948) for

the Sacramento drainage directly forced by precipitation and temperature output from three GCMs. Lettenmaier and Gan (1990) used precipitation and temperature from three GCM scenarios to force process-based basin-scale water budget models (Burnash et al. 1973; Anderson 1973) with three to five elevation band defined sub-basins, at four basins (North Fork American, Merced, McCloud, Thomes Creek) in the Sacramento-San Joaquin drainage. Jeton et al. (1996) ran a distributed parameter precipitation runoff model (Leavesley et al. 1983) to evaluate the North Fork American and East Fork Carson Rivers using specified incremental temperature and precipitation as uniform climate change scenarios. Miller et al. (1999) dynamically downscaled a GCM projection via a regional climate model and used the output as forcing to process based hydrologic models (Beven and Kirkby 1979, Leavesley et al. 1983) in the North Fork American River and the north coastal Russian River. Knowles and Cayan (2001) used historical precipitation and a single GCM projection of temperature that was statistically interpolated to a 4 km resolution as input forcing to a modified version of the Burnash et al. (1973) soil moisture accounting model (Knowles 2000) for the entire Sacramento-San Joaquin drainage.

Roos summarizes an important issue for California with regard to modeling potential changes in climate: "Because of warmer temperatures, some increase in global evaporation and precipitation are projected during the 21st century, more likely at higher latitudes. For hydrology and water resources, precipitation is the most important variable; rainfall changes in specific California regions cannot be well defined by current general circulation climate models."[138] The water sector analysis makes the following point with regard to general circulation models (GCMs) and water:

General Circulation Models and Water[139]

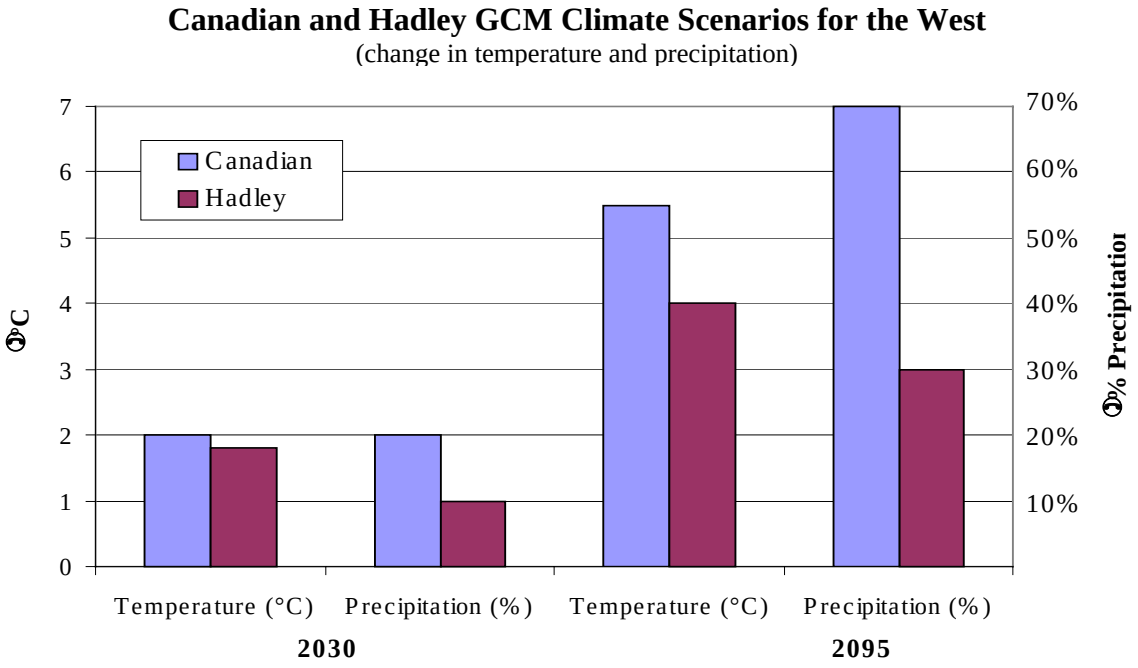
General circulation models are limited in their ability to reproduce important aspects of the hydrologic cycle. Most information available from GCMs focuses on how climate changes will affect the water balance, notably precipitation, evaporation, and runoff. Many fundamental hydrologic processes, such as the formation and distribution of clouds and rain-generating storms or watershed soil-moisture dynamics, occur on spatial scales smaller than most GCMs are able to resolve. We thus know less about how the water cycle will change than we would like to know in order to make decisions about how to plan, manage, and operate water systems. But we do know some things about how hydrology and water-management systems will be affected by climate changes and how we might strive to cope with those changes.[140]

To say that the models are limited does not mean they are not useful. Researchers are applying various models, as detailed further in this section, with important results for California.

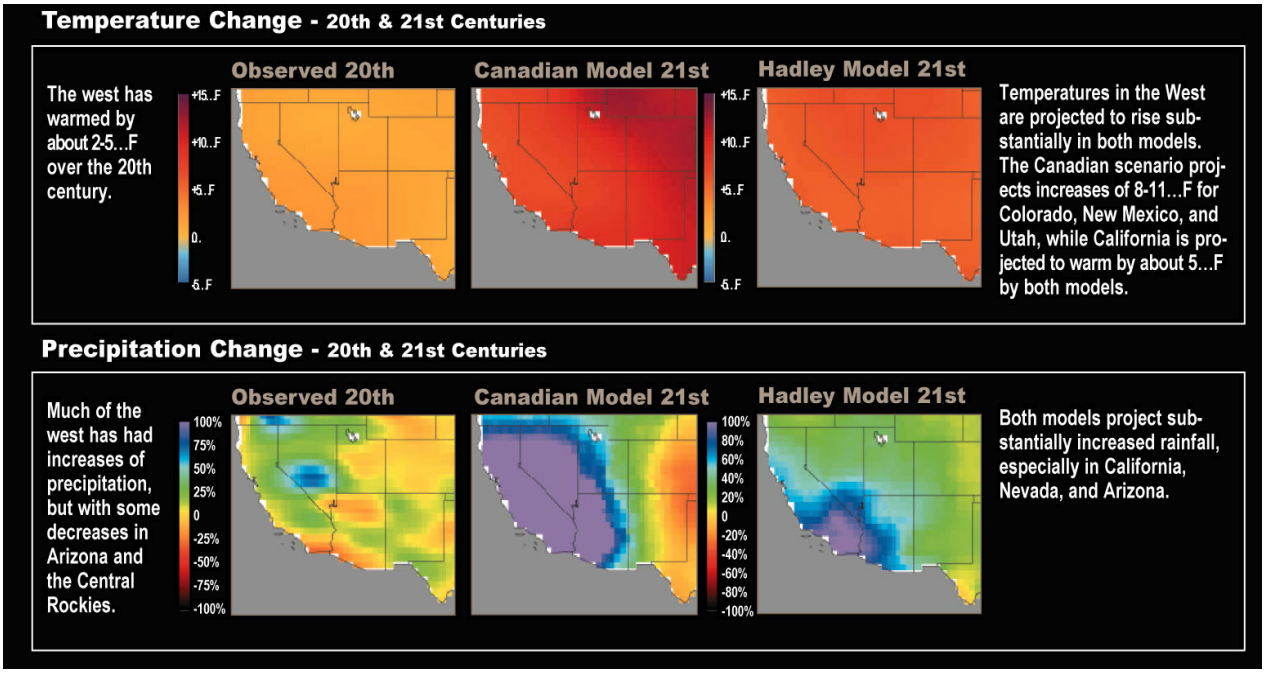
Canadian and Hadley GCMs and the National Assessment

The U.S. National Assessment is based on climate model results from the Canadian Center for Climate Modeling and Analysis and from the Hadley Center for Climate Prediction and Research (of the United Kingdom's Meteorological Office).[141] As the water sector analysis notes: "these models do reproduce much of the underlying features of our Earth's climate, and their basic structure has been proven under countless experiments and forecasts of the weather systems from which climate is usually described. … these models still remain a credible means of estimating potential future climate scenarios."[142]

Model runs for the Western United States provide the following scenarios for future temperature and precipitation:



Source: McCabe, G.J. and D.M. Wolock. 1999. General-circulation-model simulations of future snowpack in the western United States. *Journal of the American Water Resources Association* Vol.35, No.6, pp.1473-1484.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

These changes translate into the following calculations for runoff for rivers in the west, based on the model runs:

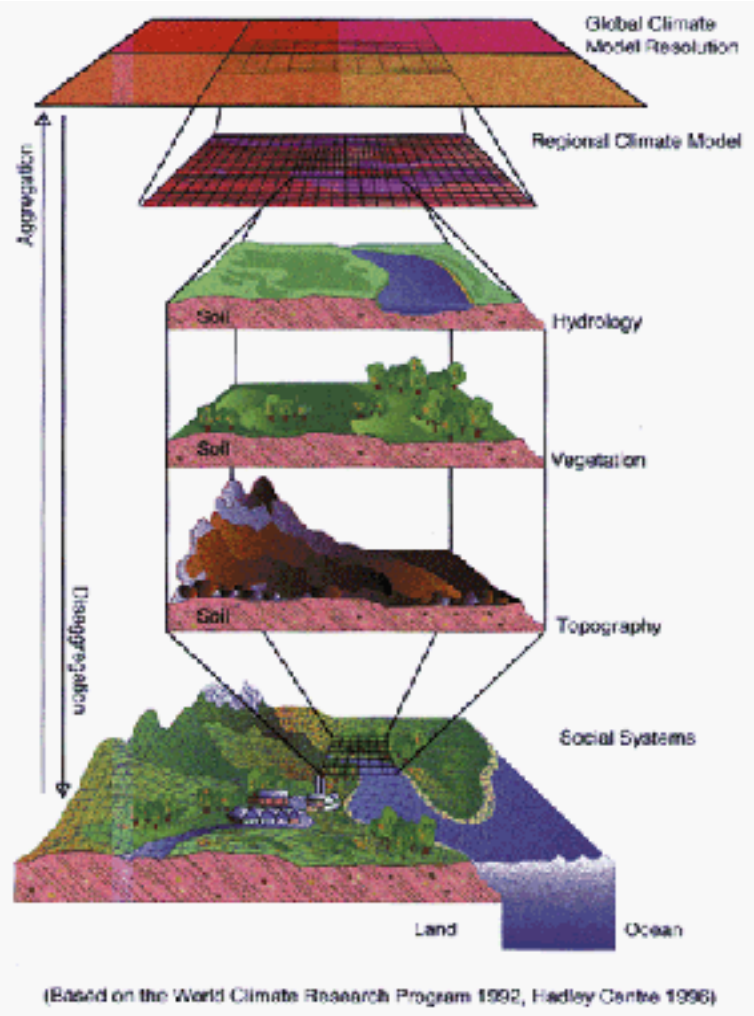
Projected Changes in Average Annual Runoff under Two Climate Models by Water Resource Region, 1990-2030 and 1990-2090
(in percent)

Water Resource Region	Canadian Climate Model 1990–2030	Canadian Climate Model 1990–2090	Hadley Climate Model 1990–2030	Hadley Climate Model 1990–2090
Rio Grande	–63	–56	–3	60
Upper Colorado	–36	5	7	66
Lower Colorado	–38	3	23	151
Great Basin	–7	75	21	138
Pacific Northwest	–2	19	15	13
California	26	139	27	118

Source: McCabe, G.J. and D.M. Wolock. 1999. General-circulation-model simulations of future snowpack in the western United States. *Journal of the American Water Resources Association* Vol.35, No.6, pp.1473-1484

Downscaling Climate Models for California

Norm Miller and the Hydroclimate and Impacts Research group at Lawrence Berkeley Lab are focusing on modeling and analysis of regional climate, streamflow, and impacts. The group is working on building an understanding of past, present, and future climate on regional and sub-regional spatial scales at various temporal resolutions. The following schematic indicates the process of layering information in the modeling.

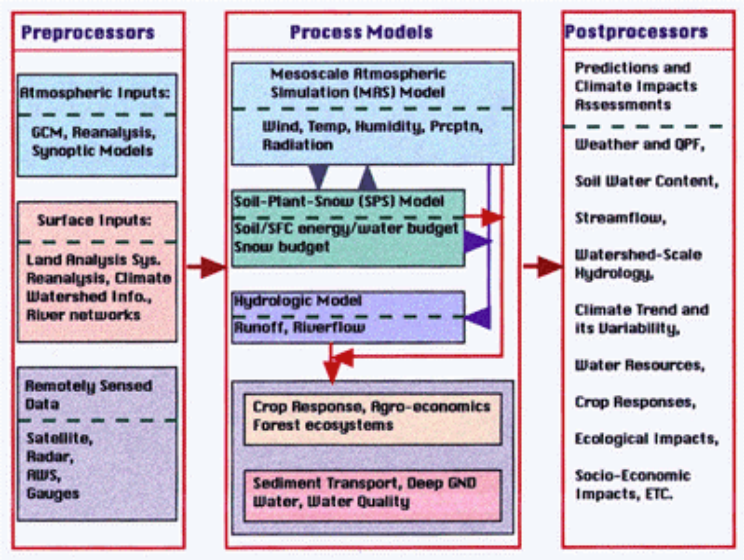


Their primary activity is the utilization of global climate historical analysis, short-term and seasonal forecasts, and long-term projected transient carbon dioxide scenarios as input forcing to our limited area mesoscale atmospheric simulation model, statistical downscaling schemes, and their suite of hydrologic models and applications. The "Regional Climate System Model" is a primary tool for the LBL research.[143]

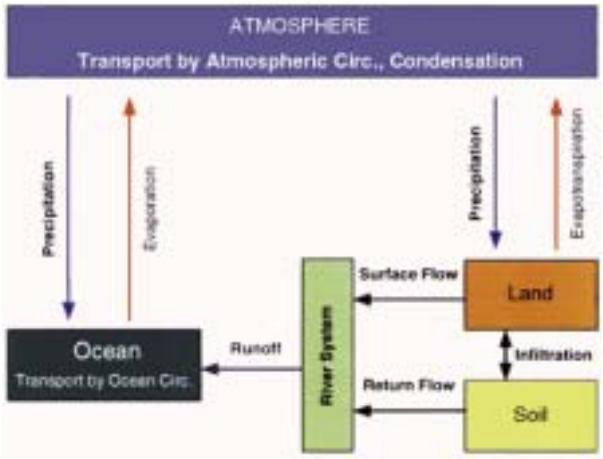
The Regional Climate System Model

Norm Miller, Lawrence Berkeley Laboratory[144]

The Regional Climate System Model (RCSM) consists of a pre-processor (input data), process models, and post processors (output data analysis, visualizations, assessments). The RCSM uses large-scale atmospheric data (GCMs, analysis, and observations) as input to produce regional-scale and river basin-scale output. Downscaling utilizes process models and statistical distributions. Downscaled global climate information can give insights to processes that occur at the regional and local scales. Coupling models for understanding climate response at a range of scales, from global climate (100500 km) to hydrologic basin-scales and scales of human impact (1100 m), is a complicated task.



Hydrologic Cycle in the Model



Climate Change May Bring More Winter Floods, and a Drier Growing Season in California[145]

Norman Miller, Kathy Bashford, and Eric Strem

Norman Miller and Kathy Bashford of Lawrence Berkeley National Laboratory, and Eric Strem of the National Weather Service's California-Nevada River Forecast Center looked at two climate change scenarios projected out to the year 2100. Based on these scenarios, they determined how the smallest to largest expected changes in regional temperature and precipitation would affect streamflow throughout California. They found that climate warming over the next century will bring potential flooding in winter, as a result of increased streamflow throughout California. The study also finds less water would be available during the summer months.

This graphic represents the six California study basins Miller and his colleagues studied to gather historic data, choosing these for their location, elevation and different climatological conditions. The areas stretch from the northern-most area to the east-central region of the state and were chosen for applications to project water demand and ecosystem response. The areas include: Smith-at Jed Smith, Sacramento at Delta, Feather at Oroville Dam, North Fork American at North Fork Dam, Merced at Pohono Bridge, and Kings at Pine Flat.

The two scenarios, both warmer and wetter than present day, were based on findings from the 2001 Intergovernmental Panel on Climate Change (IPCC) report. The report predicted temperature increases by as much as 9º Fahrenheit (F) with potential localized fluctuations in precipitation throughout the 21st century. The researchers evaluated climate change projections for three time periods; 2010-2039; 2050-2079; and 2080-2100. The projections included increases in temperature between 2.7ºF (or 1.5º Celsius (C)) to 9.0ºF (5.0ºC) and changes in precipitation from 0.0 to 30.0 percent.

Miller and his colleagues used the precipitation and temperature data from the climate change scenarios as input into the NWS "River Forecast System," which is comprised of computer models that can simulate river flow, soil moisture and snowpack.

One of the main reasons for this is that global warming will reduce the number of freezing days in the season, increase early melt, and decrease the seasonal snow storage. "The results suggest that 50 percent of the season runoff

will have occurred early in the year for many snow melt driven watersheds in the west," says Miller "and the resulting early snow melt implies higher streamflow increases and an increased likelihood of more flood events in future years."

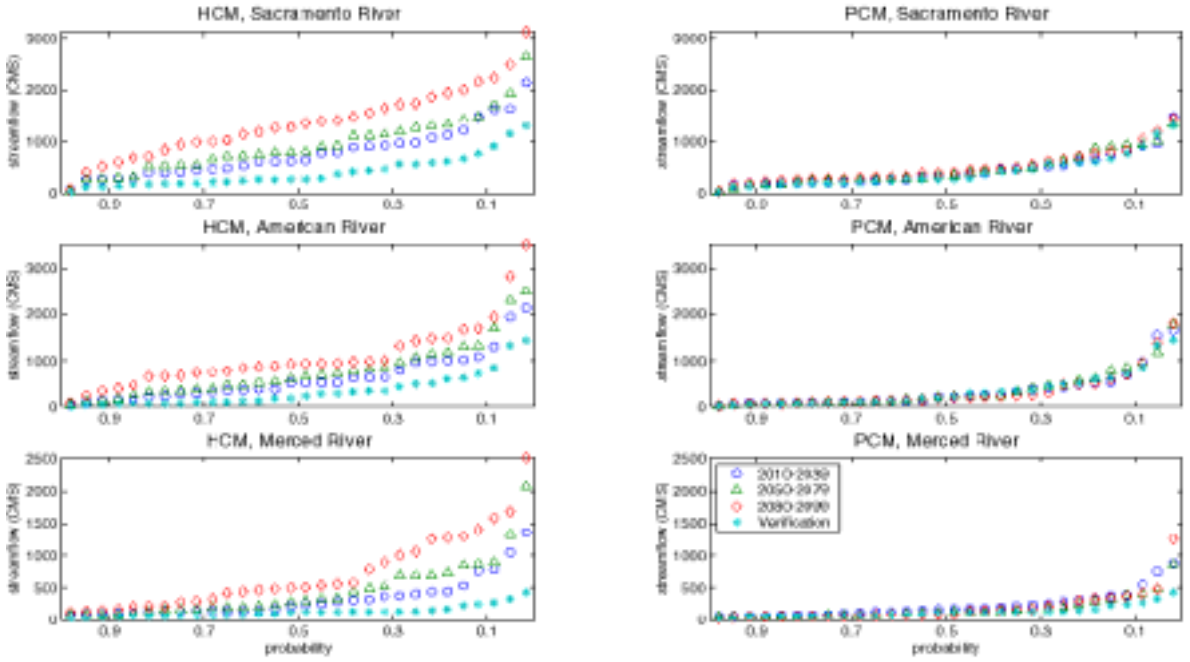
Projections of water flow are based on the amount of snow the mountainous areas get in wintertime, evident by the snowline, and the timing of the snowmelt. Precipitation in the western U.S. is primarily a winter phenomena, and in California, April 1st has been established as the date for determining the amount of water resources available for the growing season.

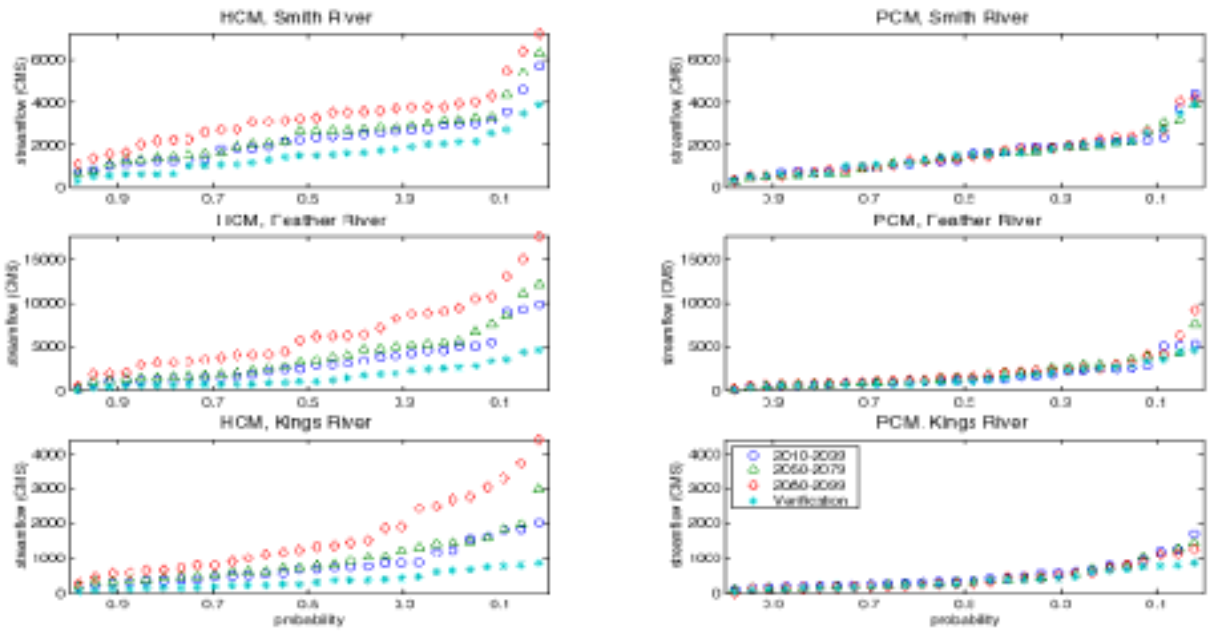
To understand how future climate change will impact water resources, it is important to understand historical climate. The researchers looked at data from 1963 to 1992 for annual high river flow and ranked them. They then applied the same technique to future climate river flows and found the likelihood of high annual flows increased. They concluded that some increased flooding could be expected regardless of the future climate outcomes, location or elevation of watersheds.

Currently there is a coordinated study underway between LBNL and the NWS to incorporate new remotely sensed satellite data with real-time flood forecasting to reduce the risks associated with floods. Miller and his colleagues used a similar approach to successfully predict the 1995 floods of the Russian River in northern San Francisco Bay area 48 hours in advance.

There were six California basins that were used for the study. The areas stretch from the northern-most area to the east-central region of the state. They areas include: Smith-at Jed Smith, Sacramento at Delta, Feather at Oroville Dam, North Fork American at North Fork Dam, Merced at Pohono Bridge, and Kings at Pine Flat. Each of these basins is represented in this figure by two charts. There are charts for two different climate model inputs (temperature and precipitation), the Hadley Climate Model 2 (HCM) and the National Center for Atmospheric Research Parallel Climate Model (PCM). The blue circles represent increases that are projected to occur between 2010 and 2039. The triangle represents increases in flow projected between 2040 and 2079. The red circles are projected increases between 2080 and 2100. The upward direction of all of these suggest increased flow and increased flooding potential early in the water year.

Charting Increased Flow In Six California River Basins





California's wet season stretches from December to March. In general, regardless of changes in precipitation during this period, the results showed snowmelt driven watersheds will experience increased streamflow up to 2 months earlier in the year, depending on the elevation of the watershed.

Evaporation and Transpiration

Increased temperatures are expected to lead to increased evaporation and transpiration which will impact soil moisture levels. The Water sector analysis notes that:

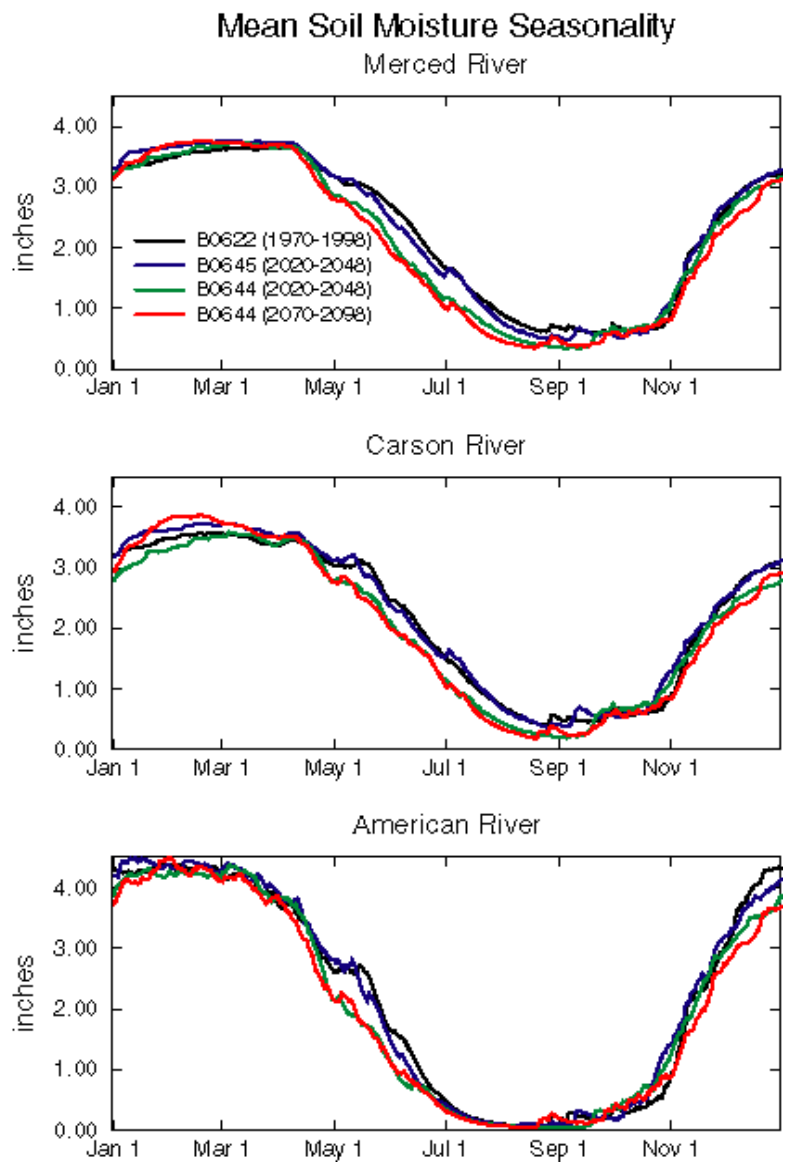
> The rate of evaporation is critical to a region's hydrologic balance. Increasing average temperatures generally lead to an increase in the potential for evaporation, though lower radiation and increased atmospheric water vapor content can reduce evaporative demands. Transpiration is also affected by a wide range of factors, including plant type and cover, root depth, stomatal behavior, and the concentration of carbon dioxide in the atmosphere. Some laboratory and field studies have shown that certain plants will decrease water use when exposed to higher carbon dioxide levels. Other studies suggest that much of this improvement can be lost if plants grow more and the increased leaf area offsets increased water-use efficiency.[146]

Michael Dettinger at USGS analyzed the potential impacts of changes in snowmelt on soil moisture at locations in the Sierra Nevada. The work parallels Miller's work above.

Soil Moisture / Snowmelt Analysis

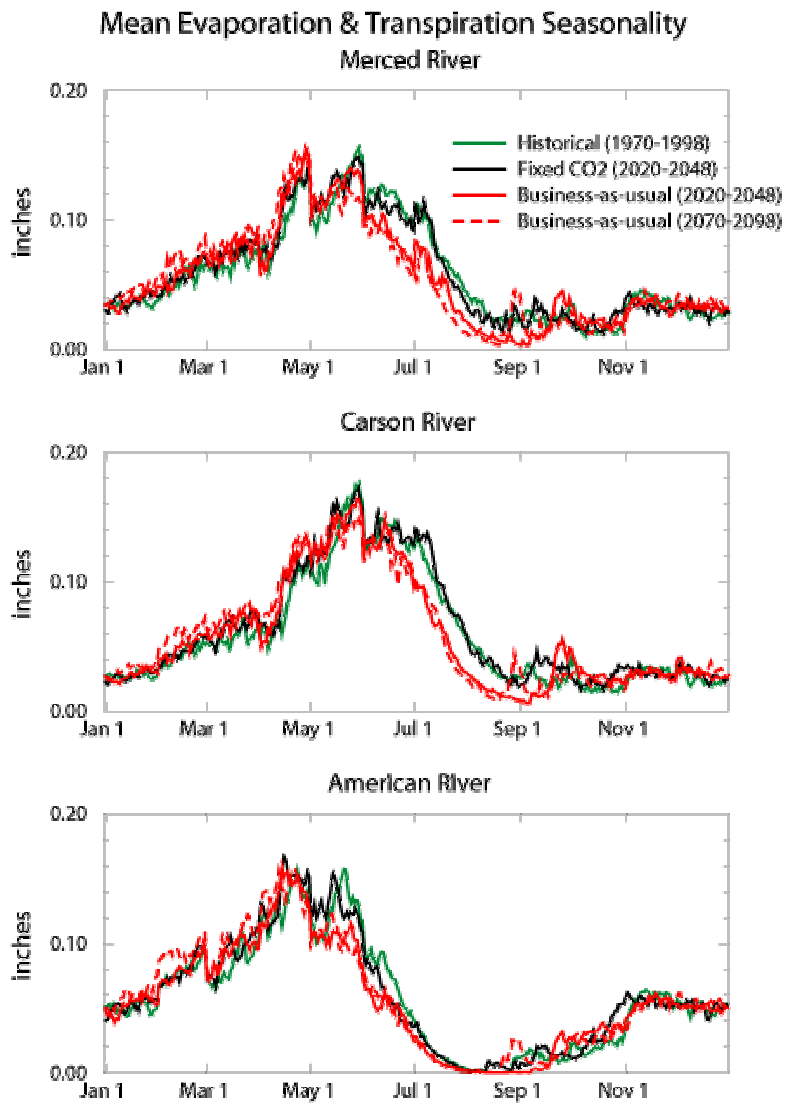
Michael Dettinger, USGS[147]

One consequence of the projected changes in snowmelt and runoff timing under greenhouse scenarios for California is that much of the water has already run out of the basins by late winter and early spring. This early runoff leaves little water in the mountain catchments (except at the highest elevations, where snows may persist) by the time of the current growing season. As a result, soil moisture levels within the mountain watersheds are projected to be much reduced, unless summer precipitation increases with climate change (which is not typically projected).



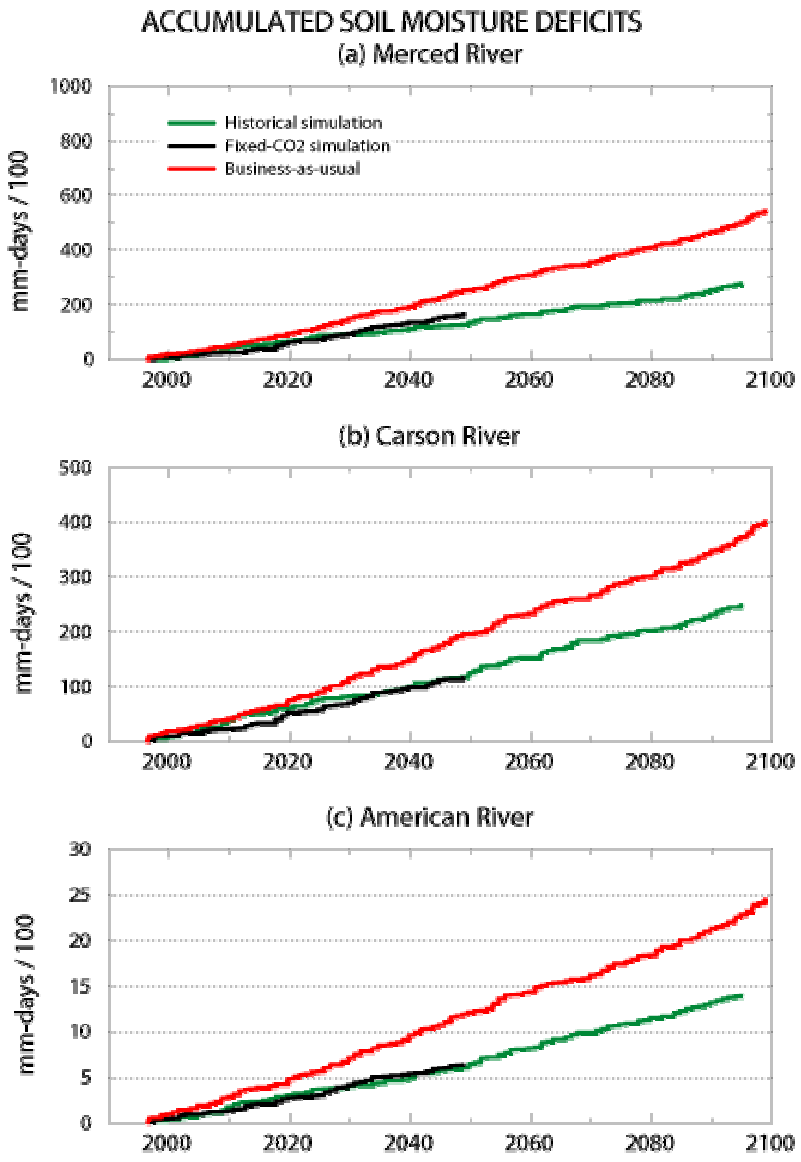
Evaporation and transpiration can be limited by decreases in the surface atmosphere's evaporative potential (which depends on things like temperatures, winds, and humidities), by a lack of moisture availability in the soil or to the

plants, and by changes in the plants themselves. In simulations of watershed responses to warming, summer soil-moisture reductions resulting from earlier snowmelt and runoff from the Sierra Nevada markedly curtail summertime rates of evaporation and transpiration from mountain watersheds. The figure below shows simulated rates of evaporation, transpiration, and sublimation from three Sierra Nevada river basins. The red traces illustrate substantial warm-season reductions in ET, due specifically to the lack of moisture in the soils. Indeed, when Michael Dettinger, USGS, re-ran these simulations with a combination of weather from today's climate in the cool season and the future warmer climate in the summer months (not shown), little change in the ET rates from today's climate resulted; in contrast, when today's summer weather was merged with the projected warmer winter and spring weather regimes, ET rates very much like those shown resulted. Thus, in these watersheds, changes towards earlier runoff may limit future warm-season transpiration much more than warmer warm-season weather can increase it. If so, then issues of whether or not CO2-fertilization or changes in stomatal resistances in vegetation may play a lesser role in determining the future of mountain ecosystems, than would be the case if summer moisture availability were unchanged.



Vegetation in many parts of California's mountain watersheds are adapted to its strongly Mediterranean climate, with its intensely dry summers. Thus, the impact of drier summer conditions under greenhouse warming on mountain ecosystems may not be determined so much by changes in the average summer condition as by changes in occurrence of unusually dry conditions. The figure below illustrates how the accumulations of extremely dry

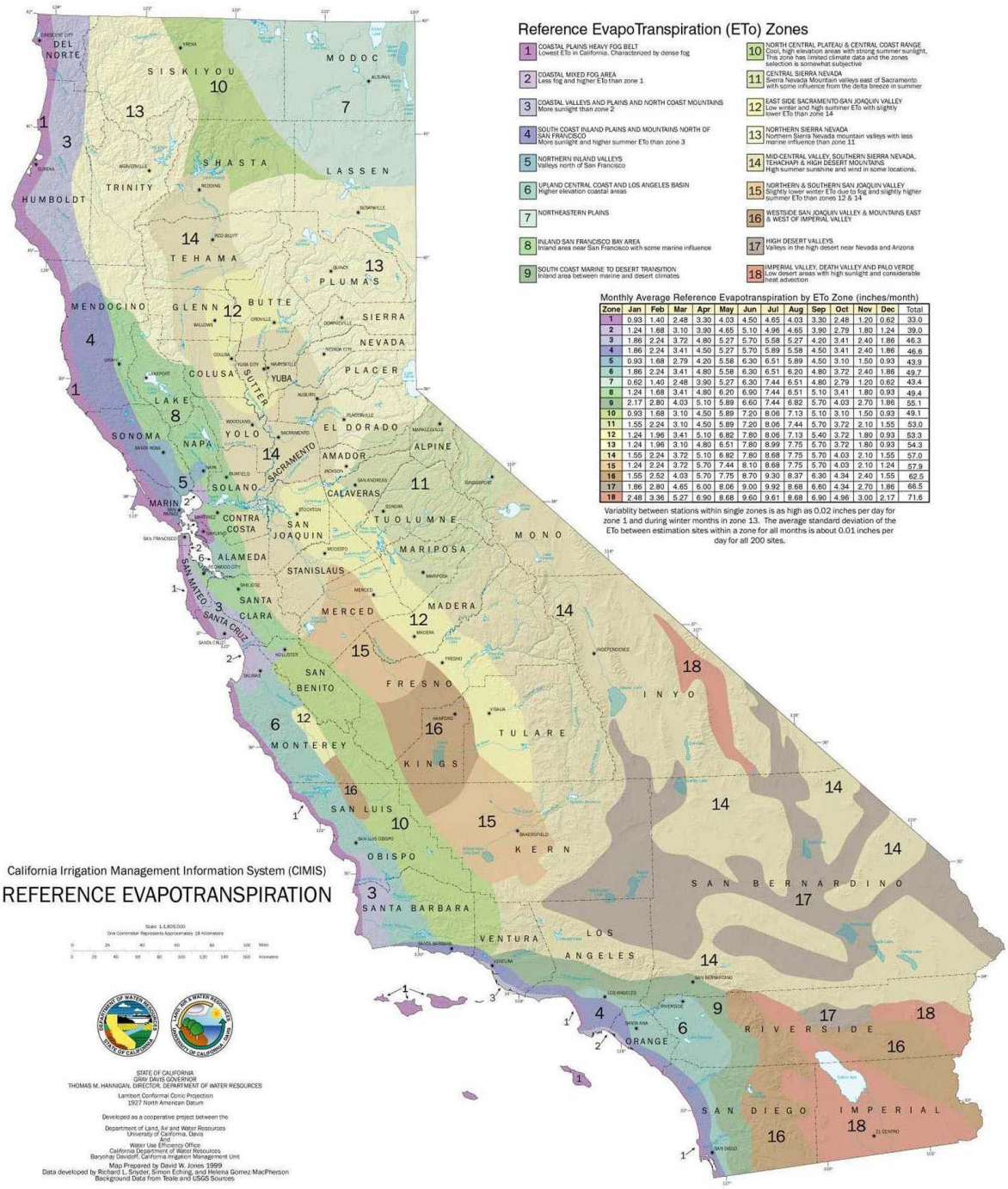
conditions could work under greenhouse warming. The figure shows the sum of all simulated daily soil-moisture excursions below the long-term average low soil-moisture values in the seasonal cycle of soil moisture in the Merced River, the Carson River, and the American River basins of the Sierra Nevada (under Parallel Climate Model simulation of historical and future climates). The faster the lines rise, the more often, and the more severely, are the simulated soil moisture levels in these basins falling below the "normal" low summer values. Clearly, in these simulations, the business-as-usual future simulations with their warmer climates result in much more soil-moisture stress within the basins. As with temperatures and floods, changes in the extremes may be amplified compared to the projected changes in the means.



The following maps from the national assessment indicate general trends on a national scale. Note the results for the southwest for the Canadian and Hadley models.

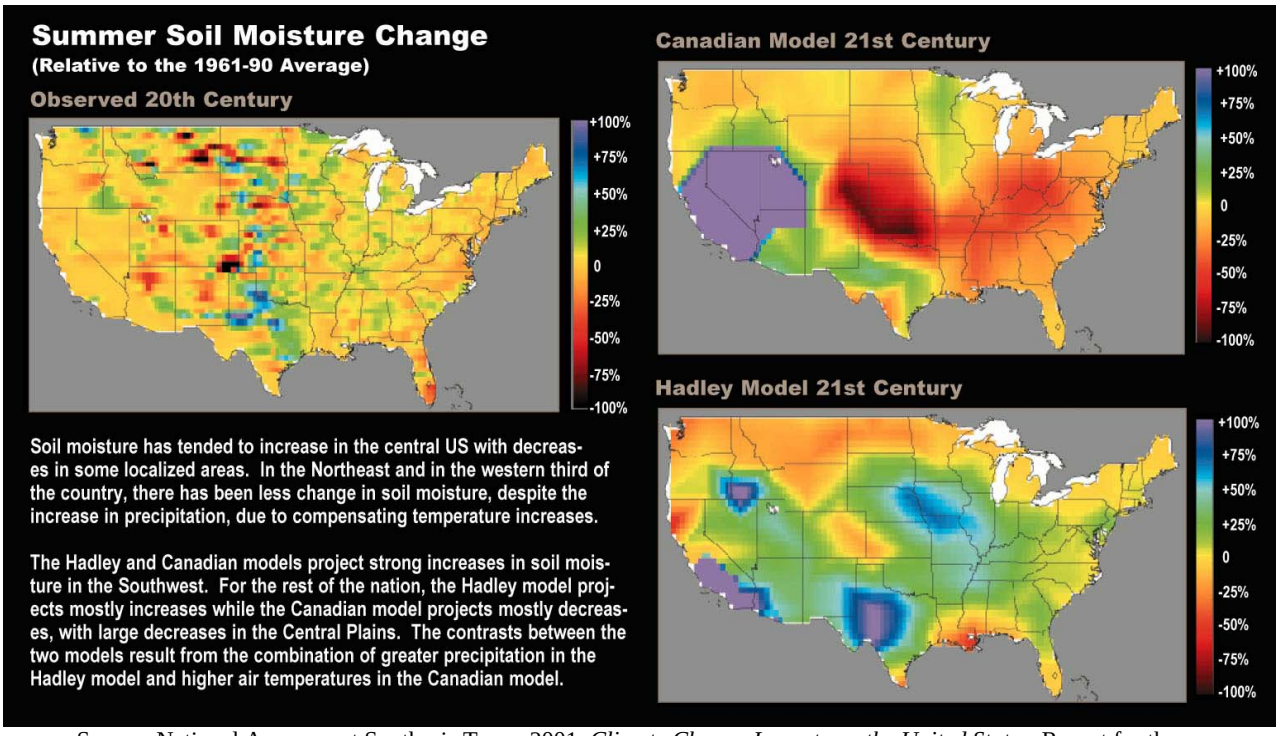
Evapotranspiration has been plotted for California as follows:

Evapotranspiration in California



Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1	0.93	1.40	2.48	3.30	4.03	4.50	4.65	4.03	3.30	2.48	1.20	0.62	33.0
2	1.24	1.68	3.10	3.90	4.65	5.10	4.96	4.65	3.90	2.79	1.80	1.24	39.0
3	1.86	2.24	3.72	4.80	5.27	5.70	5.58	5.27	4.20	3.41	2.40	1.86	46.3
4	1.86	2.24	3.41	4.50	5.27	5.70	5.89	5.58	4.50	3.41	2.40	1.86	46.6
5	0.93	1.68	2.79	4.20	5.58	6.30	6.51	5.89	4.50	3.10	1.50	0.93	43.9
6	1.86	2.24	3.41	4.80	5.58	6.30	6.51	6.20	4.80	3.72	2.40	1.86	49.7
7	0.62	1.40	2.48	3.90	5.27	6.30	7.44	6.51	4.80	2.79	1.20	0.62	43.4
8	1.24	1.68	3.41	4.80	6.20	6.90	7.44	6.51	5.10	3.41	1.80	0.93	49.4
9	2.17	2.80	4.03	5.10	5.89	6.60	7.44	6.82	5.70	4.03	2.70	1.86	55.1
10	0.93	1.68	3.10	4.50	5.89	7.20	8.06	7.13	5.10	3.10	1.50	0.93	49.1
11	1.55	2.24	3.10	4.50	5.89	7.20	8.06	7.44	5.70	3.72	2.10	1.55	53.0
12	1.24	1.96	3.41	5.10	6.82	7.80	8.06	7.13	5.40	3.72	1.80	0.93	53.3
13	1.24	1.96	3.10	4.80	6.51	7.80	8.99	7.75	5.70	3.72	1.80	0.93	54.3
14	1.55	2.24	3.72	5.10	6.82	7.80	8.68	7.75	5.70	4.03	2.10	1.55	57.0
15	1.24	2.24	3.72	5.70	7.44	8.10	8.68	7.75	5.70	4.03	2.10	1.24	57.9
16	1.55	2.52	4.03	5.70	7.75	8.70	9.30	8.37	6.30	4.34	2.40	1.55	62.5
17	1.86	2.80	4.65	6.00	8.06	9.00	9.92	8.68	6.60	4.34	2.70	1.86	66.5
18	2.48	3.36	5.27	6.90	8.68	9.60	9.61	8.68	6.90	4.96	3.00	2.17	71.6

Source: Charles Burt, 2002. Irrigation Training and Research Center (ITRC).



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

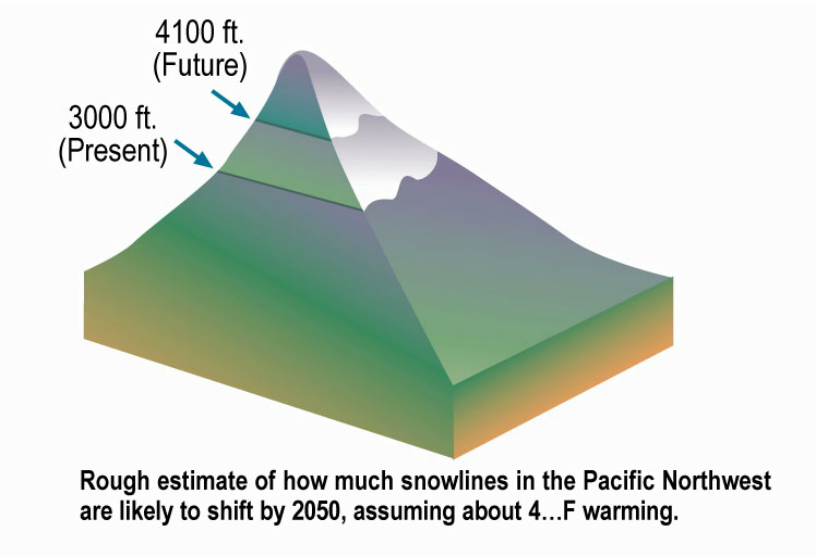
Snowpack

Mt. Shasta, Photo from DWR

Snow, and the service it provides in storing and releasing water, is of critical importance for California. From a water storage and management perspective, snow is the equivalent of several major reservoirs. Jonas Minton, Deputy Director, California Department of Water Resources,

notes that "Winter snowpack in the Sierra Nevada Mountains functions as a major water storage system. More water is stored in snow than is contained in the state's three largest reservoirs."[148]

Climate change is expected to affect snow levels. The water sector analysis found that: "A growing amount of research has established that higher temperatures will lead to dramatic changes in snowfall and snowmelt dynamics in watersheds with substantial snow. Higher temperatures will have several major effects: they will increase the ratio of rain to snow, delay the onset of the snow season, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to more rapid and earlier seasonal runoff."[149] The following schematic for the Pacific Northwest provides a simplified representation of snow level changes.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

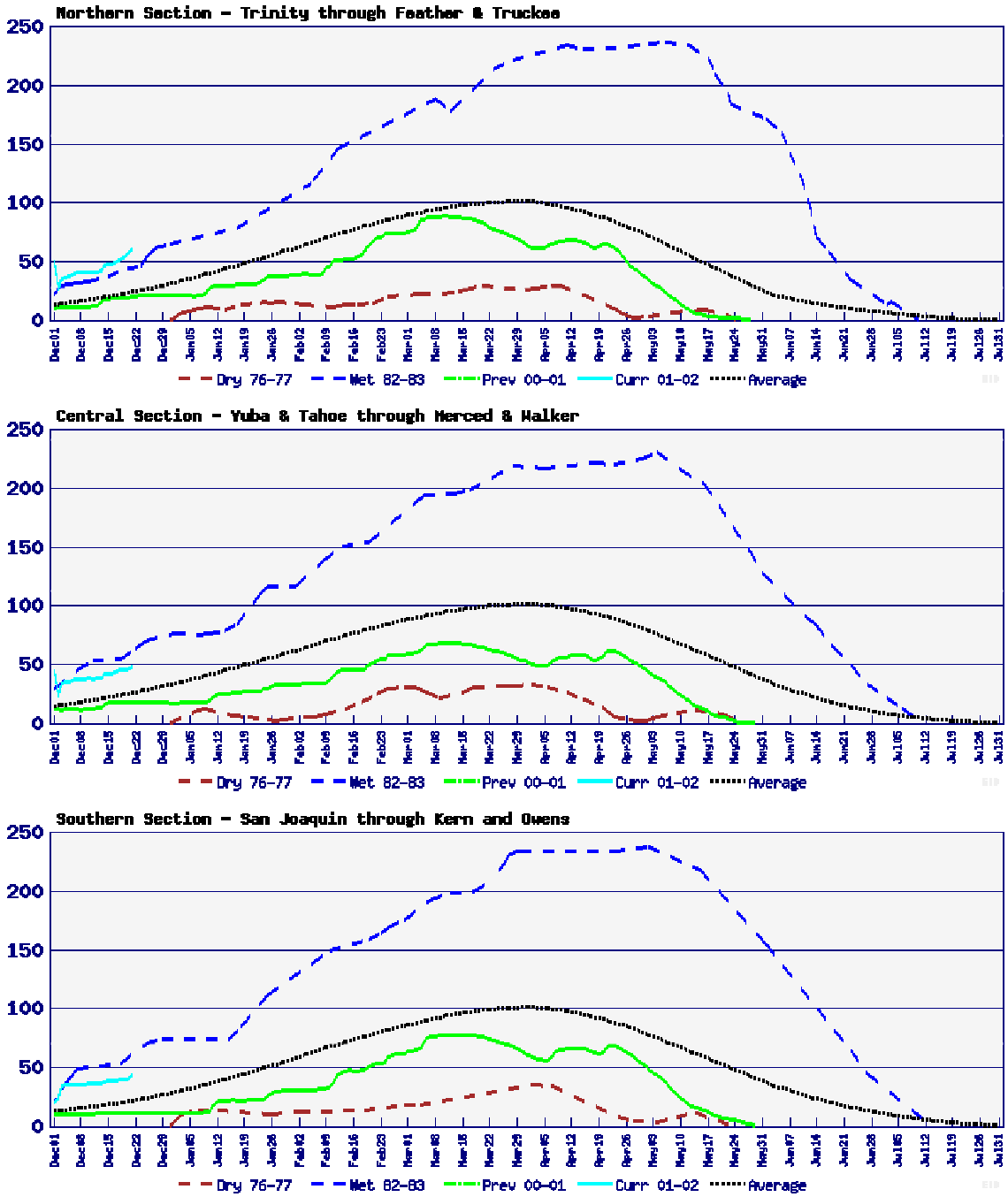
California has monitored snow levels since 1929, when the State Legislature established the "California Cooperative Snow Surveys Program" as a statewide program coordinated by the Division of Water Resources, now the Department of Water Resources.[150] DWR collects snowpack, rainfall, and river discharge data, to forecast seasonal river runoff volume. This forecast is officially published in DWR's *Bulletin 120*.

The National Assessment's water sector report focused specifically on the issue of snowmelt. "As early as the mid-1980s, regional hydrologic studies of global warming impacts suggested with increasing confidence that higher temperatures will affect the timing and magnitude of runoff in these regions and studies have now shown that all watersheds with substantial snow dynamics are likely to be affected.[151] Indeed, over the past two decades, this has been one of the most persistent and well-established findings on the impacts of climate change for water resources in the United States and elsewhere."[152]

The following graphs are a representation of snow survey data for California under different conditions.

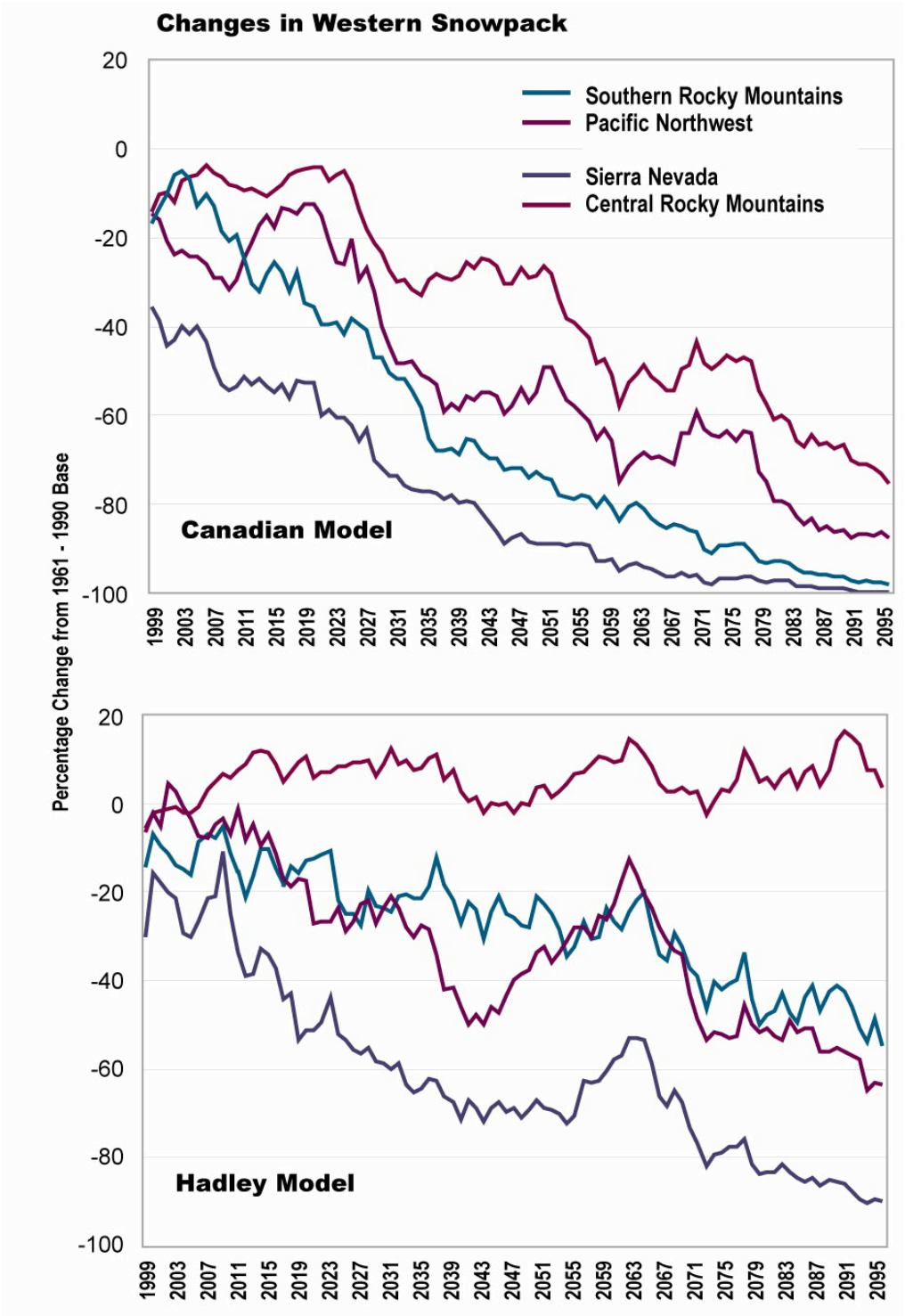
California Snow Water Content

Percent of April 1 Average, December 21, 2001



Source: California Department of Water Resources, http://cdec.water.ca.gov/cgi-progs/current/PlotSWC

Using the Canadian and Hadley models, snowpack in key mountain systems in the west is plotted out to 2095 in the following graphs.



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Simulations of the effects of climate change on snowpack in the United States have been performed.[153] The water sector analysis summarizes the research as follows: [154]

> McCabe and Wolock evaluated the links between climate conditions and snowpack for over 300 different snow sites in the western U.S., organized into major clusters around the Pacific Northwest, the Sierra Nevada, and the Colorado basin.[155] They used long-term historical records to develop a snow model that used altered climate information from GCMs. For most of the sites, strong positive correlations were found between precipitation and snowpack; strong negative correlations were found between temperature and snowpack. These correlations indicate that the supply of winter moisture is the best predictor of snowpack volume, while temperature is the best predictor of the timing of snowmelt and the overall nature of the snow season. This correlation breaks down only for those high-altitude sites where mean winter temperatures are so cold that the ratio of rain to snow is not affected.

These findings are consistent with research in California that indicates a significant impact of temperature change on snowpack.

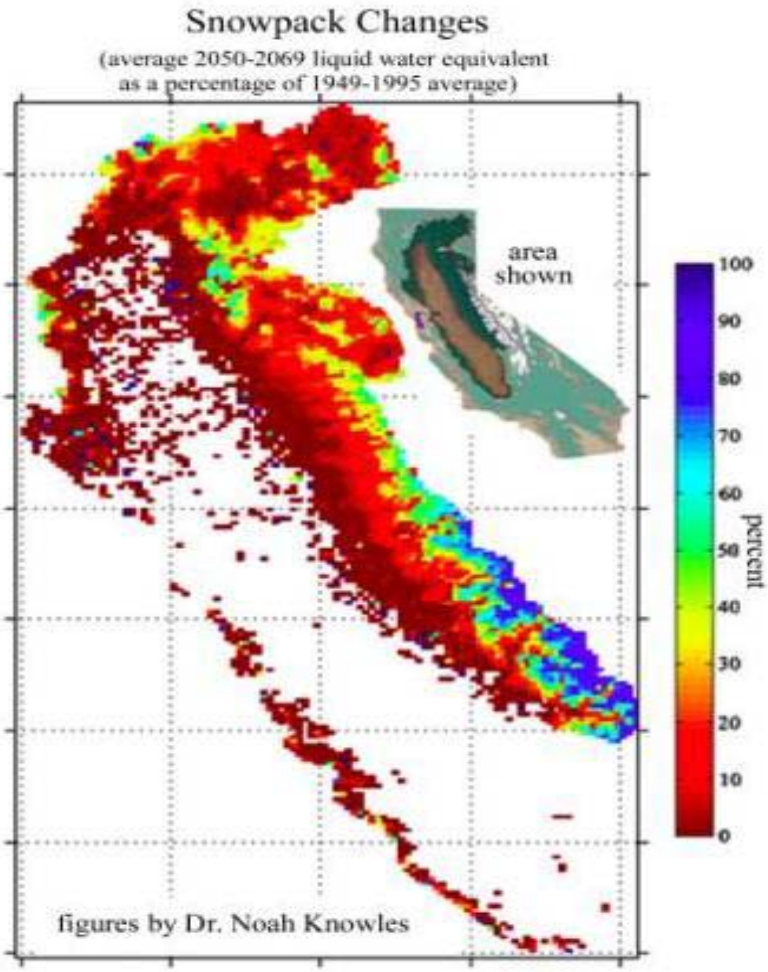
Yosemite Hydro-Meteorological Monitoring[156]

California Applications Program
Scripps Institution of Oceanography

High elevation snow accumulation and snowmelt are a crucial element of the hydrology and water supply in the western United States and yet we don't understand it very well. Some very important fundamental questions include:

- How is precipitation distributed over the various elevation zones?
- Where does it rain and where does it snow?
- Do higher elevations contribute to snowmelt later than low elevations or do they all melt simultaneously?
- How long does it take for the high elevation snowmelt to register in lower elevation stream gages?
- How do these snowmelt contributions integrate into diurnal and multi-day "signals", and how do they propagate down the river?
- What factors cause/impede snow melt?
- How do the various nutrients and other chemical species enter the river system and vary over seasons and years?

To investigate possible impacts of climate change, The Bay-Delta Watershed Model (Knowles 2000), a physically based hydrologic model of the 140,000 km2 San Francisco Bay-Delta watershed with a 4 km resolution, was used to simulate snowpack and streamflows throughout the watershed under historic and projected future meteorological conditions (see figure below).



Under a projected average warming of 2.1 deg C by 2090, the total amount of water stored annually as snow in the watershed of the San Francisco Bay-Delta estuary decreases by approximately 50%. This decrease is most severe in the low- to mid-altitude northern Sierra and Cascade ranges, with a regional loss of nearly 70% of the snowpack. This results in a strong decline in the snowmelt portion of the northern headwaters' hydrograph. These losses are also associated with a 25%-50% increase in the magnitude of flood peaks during the rainy season. While impacts are not as severe in the high Southern Sierra, nearly 40% of the snowpack is lost there, resulting in a significant loss of natural freshwater storage throughout the watershed. The projected loss of nearly 7km^3 of the watershed's natural snowpack storage would be very difficult to mitigate. Historically, the major reservoirs of the watershed have operated near capacity, particularly in wet years. This leaves little space for the management adjustments a large loss of natural storage would demand. The problem is exacerbated by the fact that under warmed conditions, flood peaks would increase dramatically and more space would need to be made available during the rainy season for flood control. This means that by the rainy season's end, reservoir levels would be relatively low with little snowmelt available for recharge in subsequent months. Under this scenario, meeting freshwater demands during the dry season would become very difficult. Flows during the rainy season would be higher and dry season flows would be much lower. In the San Francisco estuary, such changes would mean somewhat fresher rainy season conditions and much higher dry season salinities.

In view of the large interannual and lower frequency climate variability in the Sierra and to learn more about potentially large impacts due to climate change, a multi-disciplinary, multi-agency team is designing a program to install an upgraded set of meteorological, snow and stream instruments in the Sierra Nevada. In the first phase during summer and fall of 2001, a team from UCSD/Scripps Institution of Oceanography (SIO), USGS, State of California, National Park Service, and the Desert Research Institute (DRI) have laid plans to install an initial set of instruments in Yosemite National Park. Funding comes from NOAA OGP, through the California Applications Program, as well as support from the University of California CalITT^2 program and a new NSF ITR grant.

Yosemite National Park is a scientific treasure as well as a natural wonder. The park sites astride the high Sierra Nevada and encompasses the pristine watersheds of two important rivers, the Merced and the Tuolumne. Its relatively undisturbed conditions, together with the access that park roads and trails provide to the high country, make it a unique setting for scientific studies of the range. During the 2001 Yosemite Research Workshop, the Park was identified as having a special role in the earth sciences as a locus for trans-Sierran studies and for studies of the

responses of natural systems to global to regional climate change. The Park environs also have the potential to be a barometer for hydrologic variations at spatial scales spanning the range to the whole of western North America, and time scales ranging from hours to decades.

To fulfill this promise, meteorological, snowpack, and hydrologic conditions within the Park must be monitored in more detail and greater consistency than in the past, or elsewhere (at this scale) in the range. Indeed, the presence of the almost century-long meteorological stations and streamflow gauging stations in the Merced River basin have provided much of the incentive for studies that--to date--have demonstrated the remarkable potential of the Park for earth science investigations. However, these relatively few observation sites need now to be augmented with more monitoring sites, and sites monitoring additional parameters, in both the Merced and Tuolumne River basins.

This field season (summer and early fall 2001), snow and meteorological instruments have been planned for along the Tioga Road corridor traversing the west slope between Crane Flat and Tioga Pass. Stream stage, temperature and chemistry instruments are planned for at a series of sites along the Merced River in Yosemite Valley, along key sites and tributaries of the upper Merced above Happy Isles Bridge, and in several sites and tributaries to the Tuolumne River above Hetch Hetchy reservoir. Our initial concentration is to install a set of key instruments, some at existing snow, weather and stream gage locations to begin to fill in the needed spatial and physical elements to describe the hydrometeorology snow accumulation, snowmelt, and stream/watershed chemistry. At the present stage, our tactic is to collect more and better data, without too much effort to collect it efficiently; much of this data is being gathered on self-recording/not transmitting instruments or is only sampled and transmitted at relatively low data rates. In the next phase, we aim to not only add needed instrumentation, but also produce a modern communications system that will allow real time access and processing of a growing multi-sensor data stream. Thus, the system that is being designed in Yosemite aims to accommodate the needs of more and better information to monitor and understand changes that will affect not only the Park, but also the region and the Nation over the coming decades.

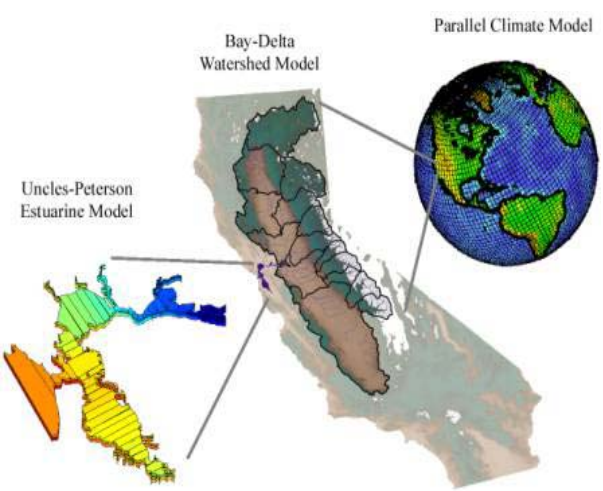
Using the analysis for hydrology and salinity, researchers at Scripps have modeled hydrology and impacts to the delta and San Francisco Bay.

Potential Impacts of Global Warming on California's Hydrology[157]

Dan Cayan and Noah Knowles
Scripps Institution of Oceanography and USGS

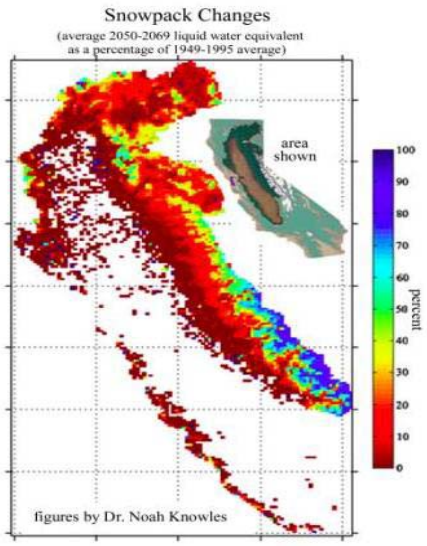
San Francisco Estuary

California's primary hydrologic system, the San Francisco estuary and its upstream watershed, is vulnerable to the regional hydrologic consequences of projected global climate change. An understanding of the potential impacts is necessary to prepare mitigation strategies. Projected temperature anomalies from a global climate model are used to drive a combined model of watershed hydrology and estuarine dynamics. By 2090, a projected temperature increase of 2.1 degrees C results in a loss of about half of the average April snowpack storage, with greatest losses in the northern headwaters. Consequently, spring runoff is reduced by 5.6 cubic km, with associated increases in winter flood



peaks. The smaller spring flows yield spring/summer salinity increases of 5 psu, with larger increases in wet years. Mitigating the impacts of climate change is likely to more difficult in wet years.

The figure to the left shows the modeling hierarchy used to assess potential impacts of climate change on the estuary and watershed. Climate change simulations from the Parallel Climate Model (PCM) are downscaled to drive the Bay-Delta Watershed Model (BDWM), yielding estimates of hydrologic impacts throughout the watershed (region highlighted). Simulated total watershed outflows are then used to drive the Uncles-Peterson (UP) model, generating estimates of estuarine impacts.



Simulated snowpack under warmed conditions depicts a severe loss of snow as indicated by changes in the snow water equivalent (SWE). By 2030, under the "business-as-usual" scenario, temperature is projected to rise about 0.6 deg C, resulting in a minor decrease in April snowpack at lower elevations. However, by 2060 a temperature rise of 1.6 deg C results in a loss of one-third of the total snowpack. This loss is focused in mid to lower elevations since the snowpack there is more sensitive to temperature changes than at higher, colder elevations. Regionally, this means that the northern Sierra and Cascades experience the greatest loss. Simulated April snow water equivalent (SWE), expressed as a percentage of average 1995-2005 SWE, for 2050-2069 is shown in the figure to the right.

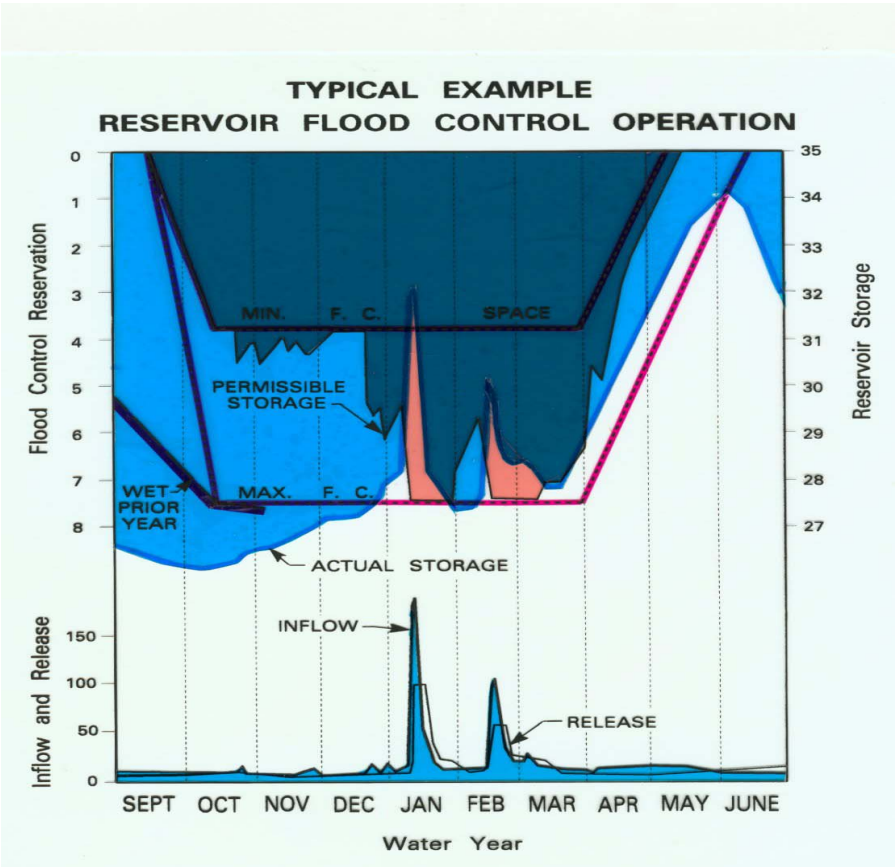
Knowles and Cayan, "Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary", to appear in *Geophysical Research Letters.*

Runoff

Maurice Roos, California State Hydrologist, Department of Water Resources, provides a review of seasonal runoff and reservoir operation:

> The large reservoirs are multi-purpose projects built to provide flood control during the winter wet season. The following shows an example of flood control operations for Lake Oroville, based on DWR operations records. The upper and lower lines are flood space requirements, less when the watershed is relatively dry and more when wet (lower line), and show how the allowable storage changes during a season. The large storm in mid-January caused a rapid change in basin wetness and allowable storage. Excess runoff was temporarily stored during the winter storm (note the sharp rise in reservoir storage in mid-January), then released after the storm. A substantial amount of winter precipitation has historically been stored in the snowpack. During the spring (late March, April, and May), flood control requirements are eased and, if all goes well, the reservoirs fill from spring snowmelt. In this example reservoir storage peaked in early June, but did not quite fill before the higher summer water demands started the seasonal draw down cycle. Potential loss of a large fraction of snowmelt runoff would make it more difficult to fill the large reservoirs in most years with corresponding

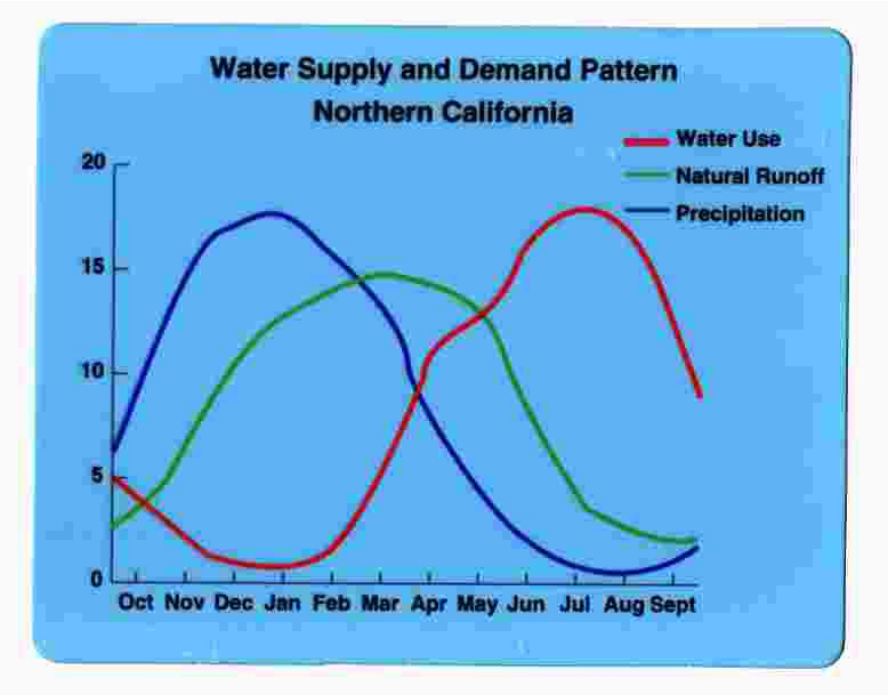
reductions in water supply yield, some losses for recreation and hydroelectric power, and possible temperature problems for downstream fisheries.[158]



Typical Example, Reservoir Flood Control Operation
Source: Maurice Roos, *DWR Lake Oroville operating records for Water Year 1980*

Roos observes that: [159]

> The more substantive changes to be expected are in the water supply sector. Higher snow levels during winter storms mean more direct rain runoff, less snowpack, and less spring snowmelt runoff. The shift in runoff patterns from spring snowmelt into winter runoff as a result of temperature increases would cause major changes in usable water from major California rivers and reservoirs especially in the lower elevation northern Sierra Nevada. The following chart from data in DWR files and operation studies, may help illustrate this point.



Source: Maurice Roos, Water Supply and Demand Patterns in Northern California

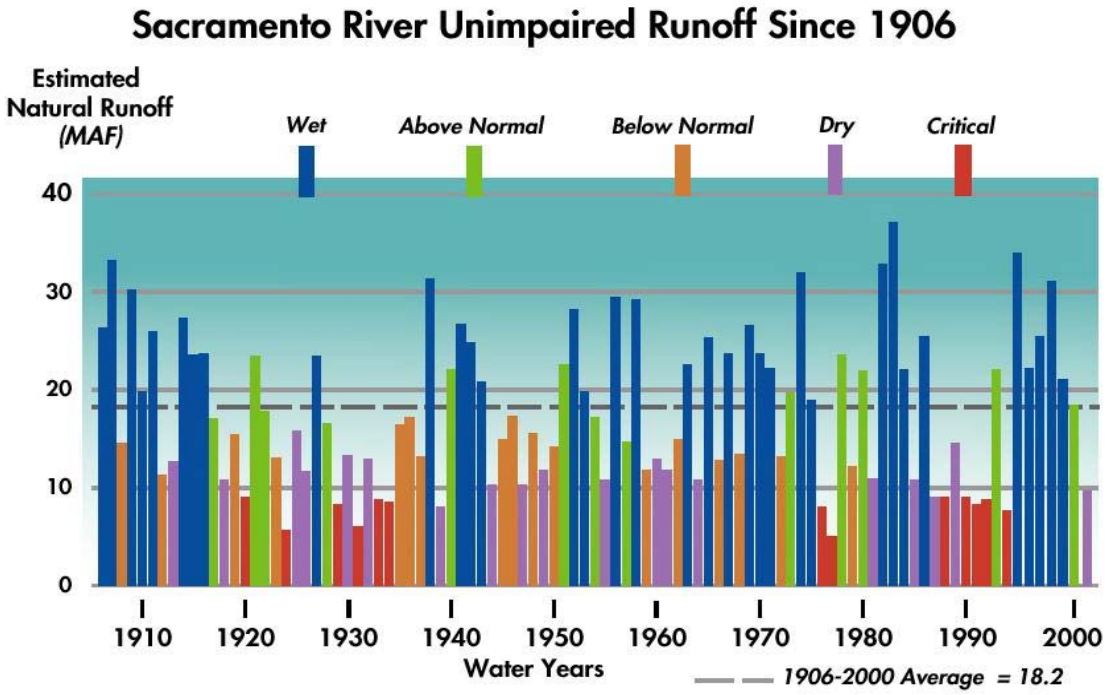
Demand Pattern

The first curve (blue line) shows the average pattern of precipitation in the northern Sierra. The peak precipitation month is January; December and February are not far behind. These three months account for half the annual precipitation. (The water year begins in October and ends in September to correspond to the normal runoff season.) Rainfall patterns are quite similar in all of northern and central California. The second (green curve) shows runoff in the Sacramento River basin. The primary reason for the lag is the natural storage of a portion of the winter precipitation as snow pack and its gradual release during the spring melting season. The red line is a typical demand for water use in northern and central California. Snowmelt runoff provides a substantial share of early demand directly; as demand rises and natural runoff decreases, stored water must be used to make up the difference. As a general rule, less spring runoff means a greater need for winter storage to provide the same annual demand. For California's major foothill reservoirs, added winter runoff often is not storable because of the need to maintain flood control space at that time.[160]

Seasonal patterns and variability in precipitation and runoff in California are the conditions upon which water planners and managers have designed the state's water infrastructure. Roos observes:

> In addition to seasonal patterns, variability in annual runoff is an important element in California water supply. Dry years are interspersed with wet years. The records of precipitation and runoff show that extremely dry periods often last several years. The following figure shows the history of Sacramento River system unimpaired runoff (sometimes called the four river index). The bars are

color coded in the 5 categories, from wet to critical, used in determining Delta water quality criteria (the 40-30-30 index). The driest single water year was 1977 at about 28 percent of average and the wettest was only 6 years later in 1983 at 207 percent of average. The driest two year period was 1976 and 1977 at about 28 percent of average and the wettest was only 6 years later in 1983 at 207 percent of average. The driest two year period was 1976 and 1977. Two six year sequences of drought stand out - 1929–1934 and 1987–1992. Many reservoirs were built to maintain a certain level of planned deliveries or reliability, should there be a repeat of the 1929–1934 drought.[161]



Sacramento River Unimpaired Runoff Since 1906. *Source: DWR Snow Surveys Program records.* (The Sacramento River runoff is the sum of unimpaired runoff from the Sacramento River at Bend Bridge, Feather River inflow to Oroville, Yuba River at Smartville and American River inflow to Folsom. Categories are based on the 40-30-30 formula.)

Roos summarizes the implications:

> Assuming no significant change in average precipitation, less spring snowmelt runoff would make it more difficult to refill reservoir flood control space during the late spring and early summer of many years, thus reducing the amount deliverable. Lower early summer reservoir levels also would adversely affect recreation and hydroelectric power. If precipitation increases sufficiently, it is

possible for snowmelt runoff to increase in the higher elevation southern Sierra water sheds. Each of these issues is worthy of further analysis and research.

Warmer temperatures are likely to lead to more extreme storm events. If anything, this would require keeping all currently available winter flood storage space in the reservoirs – if not requiring more space.[162]

These findings are consistent with the water sector analysis:

In the arid and semi-arid western United States, it is well established that relatively modest changes in precipitation can have proportionally large impacts on runoff. Even in the absence of changes in precipitation patterns, higher temperatures resulting from increased greenhouse gas concentrations lead to higher evaporation rates, reductions in streamflow, and increased frequency of droughts. In such cases, increases in precipitation would be required to maintain runoff at historical levels. [163]

Ensemble Streamflow Predictions and Reservoir Management[164]

Streamflow forecasting is critical for reservoir management. Reliable forecasts could help operators balance energy generation, mitigate severe droughts, and provide reliable flood protection. However, forecast benefits depend on the skill of the forecasting models, the way in which forecast information is presented, and whether the forecasts can be (and are) used by water managers. An ensemble streamflow prediction (ESP) consists of equally likely traces of future streamflows. The methodology is based on the premise that precipitation and temperature forcing of historical years are likely to occur in the future (Carpenter and Georgakakos 2000). ESP is most suitable for catchments with (a) strong seasonal cycles of atmospheric forcing and (b) significant persistence in soil moisture. Using this approach, a hydrologic watershed model is forced with observed precipitation and temperature up to the forecast preparation time to estimate the soil-moisture conditions at the spatial scale of the model. The model is then integrated forward in time using these soil-moisture estimates as initial conditions and the precipitation and temperature record of each historical year as input. The integration begins from the month and day corresponding to the forecast preparation time and extends out to the maximum forecast period. The result is an ensemble of equally likely streamflow traces pertaining to the forecast horizon. The ESP traces reflect the uncertainty of the atmospheric inputs but do not reflect the uncertainty of the model parameters. To incorporate this second uncertainty source, the ESP process should be repeated with different model parameters consistent with the respective parameter distributions, and the streamflow forecast ensemble should be expanded to include all generated streamflow traces.

The ESP approach has the potential to fully characterize the uncertainty of future streamflows. However, this information may or may not be utilized, depending on the nature of the management system. If, for example, reservoir operating policies are derived by deterministic management models (as are most current reservoir operating rules relating water level to release), the streamflow ensemble is usually reduced to a single time sequence such as the median or average trace, and the uncertainty implied by the ensemble is ignored. To fully utilize the streamflow forecast ensemble, the management model should be explicitly stochastic. It has been shown that ignoring forecast uncertainty in the management process can result in significant flood damage, less energy generation, and higher drought risk.[165]

Model results Folsom Reservoir operations is described in the water sector report as follows.

Folsom Reservoir Operation[166]

Carpenter and Georgakakos[167] and Yao and Georgakakos[168] investigated the response of Lake Folsom on the American River in central California to potential climate and management scenarios. Folsom's main water uses are flood control, energy generation, water supply, and maintenance of low flows for environmental quality. The modeling approach used a decision-support system that included forecast uncertainty characterization, downscaling of GCM information, ensemble hydrologic forecasting, and dynamic reservoir management in the presence of uncertainty. The assessment was based on two climate scenarios. In the first scenario, CO_2 was assumed constant, equal to its present atmospheric concentration level. In the second scenario, based on the Canadian climate model, CO_2 was assumed to increase by one percent per year.

The Canadian GCM suggests that central California will experience wetter and more variable climate under a CO_2 increase. These climate changes cause Folsom's annual energy generation and revenues (based on present energy prices) to increase by around $15 million (an increase of 24%), spillage (defined as water released above turbine capacity) to increase by 80%, and potential flood damage to increase by $219 million (using present damage cost curves). Furthermore, the study clearly demonstrates that characterizing forecast uncertainty and using it to develop adaptive management policies can drastically improve system response from disastrous to desirable. The "Ensemble Streamflow Predictions and Reservoir Management" box above describes the approach of using ensemble streamflow projections for reservoir management. For Lake Folsom, using a median deterministic forecast sequence (rather than the full forecast ensemble) under the Canadian one percent CO_2 increase scenario would cause flood damage on the order of $4.3 billion, 20 times higher than that of the full forecast ensemble ($219 million). By contrast, an improved forecast ensemble would reduce flood damage to $26 million, a 10-fold decrease. Energy generation is not adversely affected by the added flood protection, but it actually increases, as indicated by the results in the table. To establish an upper performance bound, a run was also conducted with "perfect" streamflow forecasts. In this case, flood damages can be completely eliminated, energy generation attains a maximum value, and spillage is minimized. These findings show that climate change impacts could be mitigated by changes in the way systems are modeled, managed, and operated. Under a changing climate, traditional operating rules become ineffective, while adaptive forecast-control management schemes can provide reliable coping strategies. This assessment also clearly corroborates the value of improved short term and seasonal projections.

Water Quality

Climate change will likely exacerbate water quality problems in California. In recent years, South Coast beaches have been closed repeatedly because of unhealthy levels of bacteria. The primary cause of high bacterial levels is storm runoff. Rain channeled into storm drains and backing up into sewage systems flushes bacteria, feces, pesticides, as well as motor oil and trash, into the sea. Santa Barbara County's Arroyo Quemada beach, along the undeveloped coast north of Santa Barbara, consistently has the worst water quality in Southern California,[169] attributed mainly to cattle dung and other pollutants from grazing areas. The predicted increase in runoff in a climate-altered future will aggravate coastal pollution.

Henry Vaux, in assessing the impacts of climate change on California's waters, made the following powerful statement in 1991:

> The quality of California's surface waters and groundwater is deteriorating inexorably. Toxic wastes, residues from irrigated agriculture, and shortsighted watershed management practices all threaten to reduce water quality even further. Efforts to control existing threats of water contamination have not been fully successful, and effective strategies for dealing with future problems have not been developed. The continuing degradation of California's waters threatens to widen even farther the disparity between available supplies of adequate quality and projected water demands. By permitting the degradation of water quality to continue, Californians contribute to a worsening of the future water-supply situation as surely as if they destroyed existing water-supply facilities.[170]

The water sector study identified a number of potential impacts to water quality of changes in precipitation, flow, and temperature.

> Changes in precipitation will play a crucial role by affecting water quantity, flow rates, and flow timing. Decreased flows can exacerbate temperature increases, increase the concentration of pollutants, increase flushing times, and increase salinity in arid regions.[171] Decreased surface-water volumes can increase sedimentation, concentrate pollutants, and reduce non-point source runoff.[172] Where surface runoff decreases, erosion rates and sediment transport may drop and lake clarity may increase with increased penetration of ultraviolet-B (UV-B) radiation.[173] Increases in water flows can dilute point-source pollutants, increase loadings from non-point source pollutants, decrease chemical reactions in streams and lakes, reduce the flushing time for contaminants, and increase export of pollutants to coastal wetlands and deltas.[174] Higher flows can increase turbidity in lakes, reducing UV-B penetration.

Colorado River Salinity[175]

In a study of climate change and the Colorado River basin, estimates were made how changes in flow would affect the salinity of water measured in the lower portion of the river. Salinity is already a major concern of agricultural and urban water users in the basin as well as a source of tension between the United States and Mexico. In the early 1970s, the two countries negotiated a formal agreement on the quality of water to be delivered to Mexico under the 1944 Colorado River treaty, constraining salinity and requiring the U.S. to undertake a series of land-use and water-management changes in order to keep salts out of the river. Nash and Gleick evaluated how climate-induced changes in long-term average runoff would affect salinity (defined as total dissolved solids) in the river, assuming current salinity control projects are in place and operating.[176] Even modest decreases in average runoff would lead to significant increases in salinity and violations of salinity standards, in part because of the existing difficulty of meeting those standards. A decrease in runoff of only five percent would cause the salinity criteria to be exceeded essentially all the time. While increases in average flows would be helpful, salinity criteria in the model were still violated for long periods, even with 20% increases in average runoff. If such salinity problems were to materialize, federal and state agencies would be forced to implement additional projects, even beyond those already planned, to control salinity levels in order to meet water-quality standards and treaty obligations with Mexico.

Variability and Extreme Events

The 1997-98 storm patterns attributed to the El Niño Southern Oscillation (ENSO) caused widespread destruction in California and resulted in some of the highest rainfall totals on record. Storms during February 1998 brought as much as three times the average rainfall for the month, causing 17 deaths in addition to damage to homes, businesses, roads, utilities, and crops that were estimated at $0.5 billion.[177] Saturated soils caused mudslides. Rivers and streams overflowed. Heavy storm surf eroded coastlines. Underground pipelines ruptured. Roads washed away or were obliterated by mudslides. Agricultural fields were inundated, resulting in millions dollars of lost crops. Utility lines were downed, causing widespread power outages. Telephone and other communication services were interrupted when transmission lines and transmitters were damaged by rain, wind, and mud. Some scientists believe that these conditions could become far more common, if not 'normal', in the next century if global warming continues.[178] In the not-too-distant future, the notions of one-hundred-year and five-hundred-year floods may completely lose their meaning and usefulness as planning tools. Some suggest they already have. Floods now gauged to have a one-in-500 or one-in-100 chance of occurring every year are likely to occur more frequently.

Variability, Storms, and Extreme Events[179]

Increases in extreme precipitation events recently have been projected in nested regional models over the United States,[180] and in a high-resolution nested hurricane model over the north-west tropical Pacific.[181] In a recent global model simulation with doubled CO_2, precipitation extremes increased more than the mean (the mean increase was 4%; 20-yr extreme precipitation event return values increased 11%) with a decrease in the return period of 20-yr extreme precipitation events to 10 years over North America .[182]

General studies on climate change and storminess note that there are two possible conflicting effects on extratropical storms. Some model projections of CO_2 -forced climate change suggest that storms in a climate-changed world should, on average, be fewer in number but stronger in intensity. Enhanced warming at high latitudes near the surface leads to reduced meridional temperature gradients in the lower troposphere and hence fewer storms. In contrast, more warming at the surface than aloft and a wetter atmosphere arising from increased latent heating should result in reduced atmospheric stability, increased convection, and a more vigorous hydrologic cycle, which might support more storms and perhaps more intense storms as well .[183] Combining these processes, Lambert[184] found that earlier scenarios from the Canadian model produced fewer, but more intense storms, on a global basis. Other model studies have also suggested that higher CO_2 levels might produce more intense storm events.[185]

Hayden[186] also evaluated the Hadley climate models runs for 2030 and 2095 (the Canadian model results were not available at the time). Storm occurrences are calculated from the low-pressure systems or other model outputs (such as variances in geopotential heights). Extratropical storms are an important cause of beach erosion and flooding of wetlands with saline water and they provide essential precipitation that drives much of the hydrological cycle in middle and high latitudes. Using these model output data, Hayden found no sensitivity of North American storm tracks to increasing CO_2 . The author notes the need for better regional resolution of storm tracks, particularly in the western U.S.[187] He concludes, however, that GCMs remain the best tool for ultimately accounting for the effect of greenhouse-gas accumulations on storms and recommends that this capacity in model development should be further refined.

The ramifications of the increase in severe storms associated with climate change on the insurance industry and its customers could be vast. Taxpayers, homeowners, businesses, farmers,

and utility companies will bear the brunt of the costs of weather disasters. Most insurance policies do not cover flood damage, and California insurance companies haven't provided homeowner coverage against mudslides since the 1950s because of the high risk of huge losses. (Lloyds of London is the single exception, and they have reportedly not written a single policy in California due to the high cost of the coverage.)

Recent research on patterns of climate variability, including the El Niño/La Niña (ENSO) events and extreme precipitation events, reinforce the evidence that variability must planned for, even in the absence of climate change.[188] The water sector analysis observes that: "This research consistently notes that the hydrological 'baseline' used by water planners and systems designers cannot be assumed to be constant, even without climate changes. It also helps to identify vulnerabilities of existing systems to hydrologic extremes and provides information that should be useful to those interested in the issue of adaptation and coping."[189]

Timmermann et al. suggest that the frequency of El Niño events may increase due to greenhouse warming. [190] The water sector report commented on this research as follows:[191]

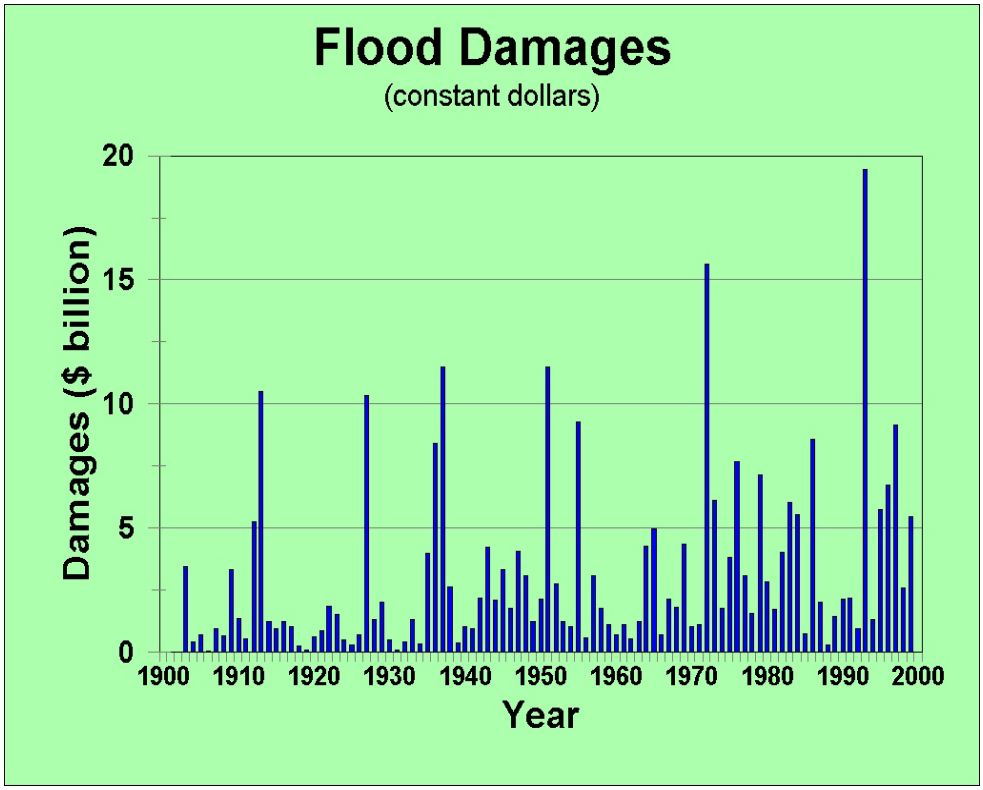
> The team used a high-resolution global climate model to simulate the El Niño/ Southern Oscillation phenomenon (ENSO) under conditions of warming. Their model indicated that the tropical Pacific climate system would undergo systematic changes if greenhouse gas concentrations doubled. *In particular, their results suggest a world where the average condition is like the present-day El Niño condition and events typical of El Niño will become more frequent.* Their results also found more intense La Niña events and a stronger interannual variability, meaning that year-to-year variations may become more extreme under enhanced greenhouse conditions. More frequent or intense El Niños would alter precipitation and flooding patterns in the United States in a significant way.

The interactions between climate change and ENSO are not fully understood. Michael Dettinger notes that at present, such responses may be model-dependent, and the actual response of the ENSO system remains uncertain. Whether there are more El Niños, or more El Niño-like climate conditions prevail, or instead the climate changes without substantially changing the role of ENSO in California's weather, California's climate can be expected to continue to be highly variable on year-to-year and decade-to-decade time scales. Climate change trends will be superimposed upon the usual (at least) vigorous climate variability that afflicts California's water systems.

Floods

Floods are responsible for significant loss of life and property. In the U.S., damages from floods have been increasing by about one percent per year. The following graph from NOAA indicates flood-related damages in the U.S. for the 20th century (in 1997 dollars).[192]

It is not clear in what ways increasing global temperatures is affecting storm patterns and extreme events. Bruce Hayden, examined storm data for a time period of over 100 years, from 1885 to 1997. He found that the data, which he broke down into 180 grid cells, failed to reveal any clear pattern of systematic increases or decreases in the number of storms over the period.[193]



Source: National Weather Service (NWS). 1999. Hydrologic Information Center.

Climate Patterns and Oscillations

Researchers are also studying the impacts of oscillations and patters in climate systems and their impact in extreme events. These patterns range from years to decades and longer. The following case study by Dettinger and Cayan looks at flood frequencies and the Pacific Decadal Oscillation (PDO).

The Pacific Decadal Oscillation and Flood Frequencies in the United States[194]

Mike Dettinger and Dan Cayan,
U.S. Geological Survey and Scripps Institution of Oceanography

Inter-decadal variations of the climate of the North Pacific Ocean basin have been categorized by the first principle component of monthly sea surface temperature patterns there, an index commonly called the Pacific Decadal Oscillation (PDO). As during El Niños, when PDO is in its positive phase, the central North Pacific is cool and the waters along the west coast of North America are warm; negative PDOs indicate a preponderance of the opposite temperature pattern. The PDO tracks climate variations that in part are distinct from, and complementary to, the tropical climate variations of the El Nino-Southern Oscillation (ENSO) process. Together the PDO and ENSO climate variations make significant contributions to year-to-year streamflow variability in North America. In order to identify possible PDO influences on the occurrence of floods, statistics describing the magnitude of floods the magnitude of floods with 5- to 50-year return intervals have been analyzed in daily streamflow series from over 1100 gauging stations in undisturbed river basins across the conterminous United States.

In 34% of the flow records analyzed, the estimated magnitudes of 5- to 50-year floods, calculated from annual maximum daily flows in years during which a 5-yr moving averaged PDO index is positive, are significantly different (at 99% confidence level) from the corresponding flood magnitudes during years in which the averaged PDO index is negative. When the PDO is in its positive phase, for example, the 20-year floods in the northwestern rivers are +18% larger and the 20-year floods in the southwestern rivers are -34% smaller than when PDO is negative. November-March floods appear to reflect PDO status most in the northwest coastal rivers and through the interior southwest; April-October floods reflect the PDO status most in the interior northwest. In order to use such statistics for prediction of flood probabilities, and in recognition of the rapid response of atmospheric circulations and fluxes to sea surface temperature variations, the corresponding statistical analyses were repeated with a version of the PDO index that can be estimated from immediately antecedent sea surface temperature variations. Flood frequencies are almost as strongly conditioned by this concurrent estimate of the decadal PDO variations as by the retrospective PDO estimates, which encourages a new set of long-lead forecasts of flood-frequency variations in rivers throughout the country.

Redmond examined flood frequencies on the American River in the context of climate change in the next case study.

American River Flood Frequencies: A Climate-Society Interaction[195]

Kelly T. Redmond
Western Regional Climate Center
Desert Research Institute, Reno, Nevada

1. Introduction

The American River flows westward from the crest of the Sierra Nevada above Lake Tahoe to its confluence with the Sacramento River in the city of Sacramento. The North, Middle and South Forks meet upstream from Folsom Dam, located on the upstream outskirts of Sacramento. Folsom Reservoir is drafted each winter to create enough flood control space to absorb a heavy runoff event.

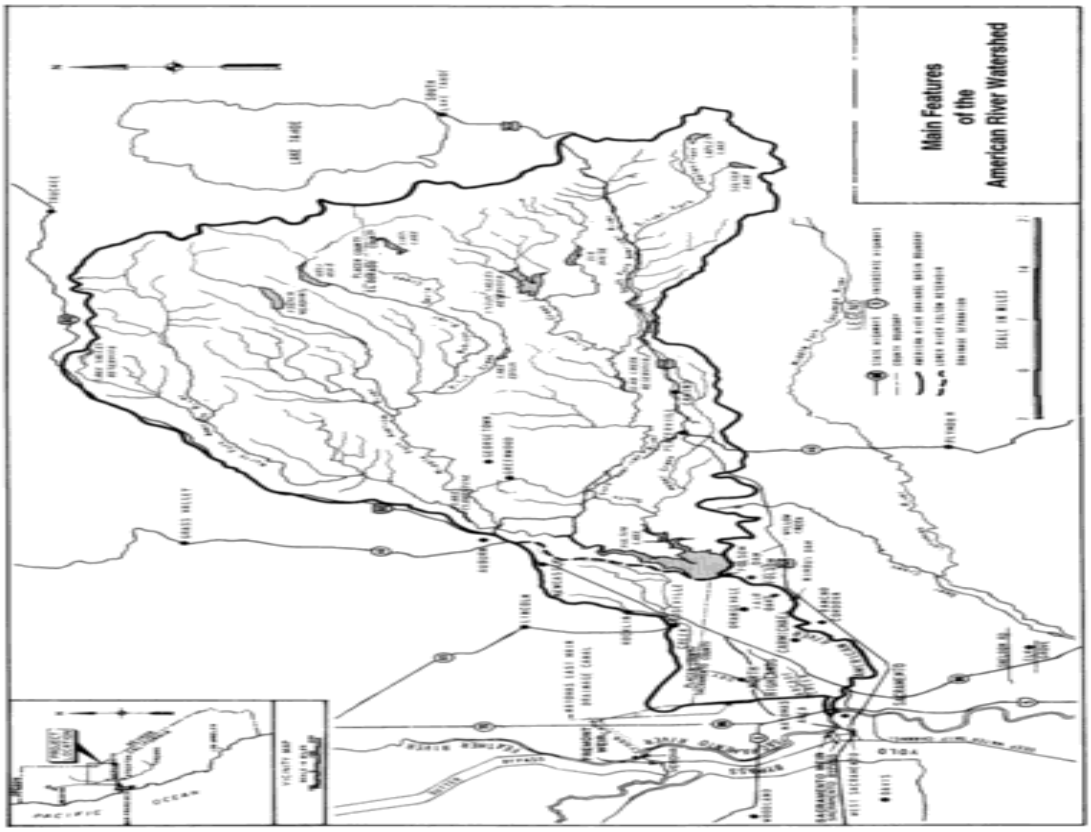
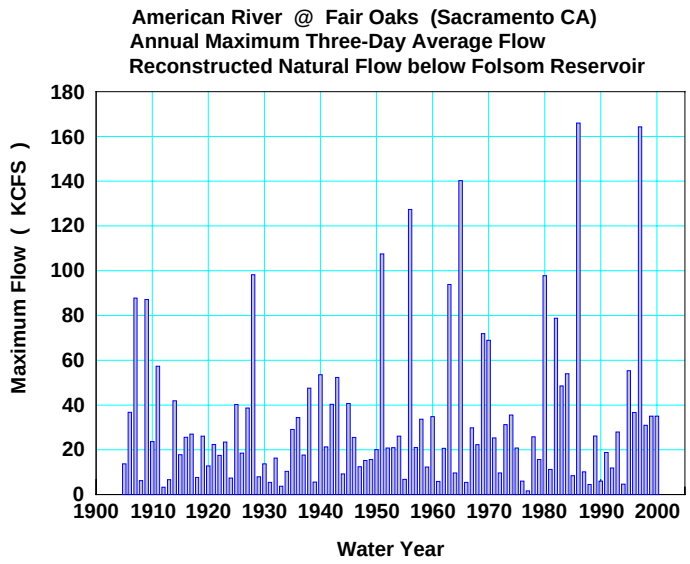


FIGURE 1.1 Main features of the American River watershed. SOURCE: Sacramento District, USACE, 1991.

A typical very heavy flow event will take 2-3 days to fill this space, so flood managers use maximum annual 3-day average flows rather than peak instantaneous flow to track year-to-year behavior. The reservoir was sized according to flood statistics from 1905-1949. Since 1950, the river has experienced seven 3-day flow values exceeding 90,000 cubic feet per second (90 kcfs), compared with once from 1905-1949, a value of 98 kcfs in the winter of 1927-28. The latter period includes the two largest, 167 kcfs in February 1986 and 164 kcfs in January 1997, only eleven years apart. What was originally thought to be "500-year" (return interval) flood protection is now estimated to be 75-80 years.

Approximately $40 billion in damageable property lies behind the levees in the city, including the state capitol building and numerous government offices. In reaction the apparent shift in flood risk, a long-running and spirited

community debate has developed over what actions to take. Options include any or all of: increasing the capacity of Folsom Reservoir, increasing the outflow capacity of Folsom Reservoir, increasing the levee system capacity, relocating residents and businesses from parts of the floodplain and limiting future development in the floodplain, and building a new dam near Auburn on the largely unregulated North Fork. None of the options are cheap, some are controversial, and all choices will depend upon estimates of the risk of various sizes of floods. The issue thus turns back to what the climate system will, or could, bring in coming decades.



2. Flood Characteristics

The American River above Folsom Reservoir drains about 1862 square miles. Topography ranges from about 10,000 feet at the highest elevations to about 10 feet above sea level at its termination. Each of the three tributaries is 80-85 mi long, and has incised deep V-shaped canyons with gradients averaging about 100 feet per mile. Travel times are approximately 18 hours from the upper basin to Folsom Reservoir. Flood peaks from the three adjoining forks arrive almost simultaneously. Large floods are almost exclusively winter events, produced by sustained moist, rapid southwest flow originating in the subtropics, with high freezing levels and thus rain to high elevations (e.g. Redmond and Pulwarty, 1997). Some degree of snowmelt is often present, but rain on saturated soil provides the bulk of the runoff. Flow is oriented nearly perpendicular to the topographic ramp formed by the western slope of the Sierra Nevada. With a stationary pattern, orographic lifting provides a mechanism for prolonged heavy precipitation. Nearby drainages including the Sacramento River are also often in flood at the same time.

3. Climate Non-Stationarity

Flows are measured just downstream from Folsom Reservoir at Fair Oaks. Reconstructed natural 3-day annual maximum flows (i.e., adjusted for upstream storage) show a decided increase from the first to the second half of the 20th Century.

The change in mid-century is not simply a peculiarity of this one gage or basin. Precipitation gages at various elevations in and near the basin show a similar increase in both the number of wet years and in the maximum 3-day and 10-day totals within each winter. The California "8-station index" (covering most of the Sacramento River drainage) shows similar temporal behavior. Interestingly, the annual precipitation is increasing more slowly or not at all. The most recent two decades have brought an increase in both the number of wet years and the number of dry years. Thus, variability has increased. Floods on the eastern slopes of the Sierra, facing the Great Basin and caused by the same factors, also show an increase over the past several decades. Thus, there is little doubt that the flood frequency increase on the American River is real.

In addition, another change was first noted by Roos (1991), and later elaborated by Dettinger and Cayan (1995). The fraction of the annual runoff from the central Sierra that occurs in late spring has been decreasing for approximately

the past 50 years. Relatively more of the annual runoff has been occurring in the winter. Winter and spring temperatures have become warmer in the central Sierra. This has been a more gradual trend rather than an abrupt transition.

4. Assessing Future Extremes

In flood frequency analysis, past records are used to assess the likelihood (return interval) of various magnitudes of precipitation and runoff over a range of durations (IACWD, 1982). What is needed is an estimate of what these statistics will be during a time span of interest in the future. This essentially amounts to a forecast of the return interval regime that will apply during that time. This time span is likely to be on the order of a generation or two, about a half-century. This is less than the expected lifetime of control structures, but by that time a new set of societal values is likely to have evolved, with these issues brought up again for re-examination from new perspectives.

The traditional approach has been to use whatever data are available from the past to form these estimates. A dilemma is encountered, however, when the recent record (in this case, the past 50 years) is decidedly different from the previous record. What portion of the past is most likely to be representative of the next half century or beyond? One is thus led into a consideration of the possible causes of climate variability in this region on decadal time scales. Of particular interest is whether these variations range back and forth between approximate extremes, or appear as monotonic or unidirectional trends. Natural climate variability is generally considered to resemble the former, and possible human-induced changes are usually considered to resemble the latter.

Among the natural kinds of variability are the two phases of ENSO (which produce different responses in the California cool season), regimes and decadal oscillations in the north and central Pacific (e.g., Pacific Decadal Oscillation, PDO), regimes of ENSO behavior (predominance of one phase over the other, etc.), possible modulation of ENSO effects by the PDO, thermohaline circulation variations in the world ocean, and others only imagined, or dimly known or understood at this point.

Among the possible anthropogenic sources of variability are greenhouse gasses (GHG), aerosols, and land use changes around the earth. One expectation from GHG is for a more vigorous hydrologic cycle with more instances of extreme precipitation events (Karl and Knight, 1997). GHG responses are often expected to gradually increase in a unidirectional manner (although this need not necessarily be true in such a highly nonlinear system), whereas aerosols and land use changes could lead to many possible non-linear and non-local responses (e.g., Pielke et al, 1998).

5. What Next?

It is against this uncertain climatic backdrop that expensive decisions with potentially lasting effects must be made and defended. While physical scientists debate whether changes are taking place in the climate system, other changes are taking place in the societal value system. Views have increasingly migrated toward favoring free-running rivers, less reliance on structural solutions to flood problems, and greater reliance on behavioral solutions, such as staying off the flood plain and de-emphasizing the placement of permanent and valuable structures there (Mount, 1995). It seems likely that these societal values will continue to change even as the climate changes or varies. Although there are strong opinions on both sides about the relative desirability of behavioral versus structural solutions, the eventual path finally chosen would likely consist of a mixture of actions which preserve some flexibility for future actions.

The problem of whether the current flood regime will continue, or grow, or will relax back to values frequently seen during less active periods in the paleo records (e.g., Meko, 1998), is thus a central focus of attention.
No firm decisions have yet been made as of this writing. However, the issues are not unique to the American River. Webb and Betancourt (1992) have pointed out analogous issues in southern Arizona. Similar problems are likely to be encountered by other cities as they reassess the relationships with their rivers.

The following analysis by Michael Dettinger shows the number of days in which flows in two Sierra rivers are simulated to exceed some relatively high rates (relative to the flows typical of

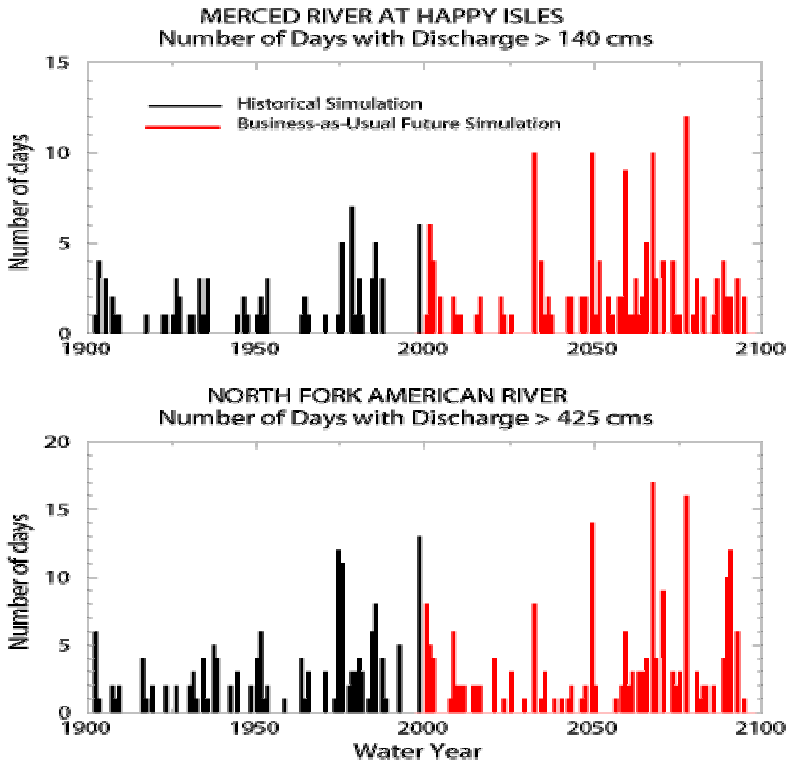
those rivers – roughly the 2- to 3-yr flood levels in each case). It is based on simulations of responses to the ACPI scenarios, which have only modest precipitation changes.[196] Thus, the changes shown are almost strictly a response to warmer temperatures. The other figure plots annual-maximum-daily floods in the Merced at Happy Isles versus the day of year that they occurred on; this simulation is from the National Assessment HadCM2 scenario, and thus is both warmer and much wetter than today.

Flood Simulations for Sierra Rivers
Based on ACPI and HadCMs Scenarios

Michael Dettinger, USGS[197]

Climate changes associated with increasing greenhouse gases could affect Californian flood regimes both by providing more warm wet winter storms (including more rain-on-snow floods) and by providing more large storms. The potential for such changes is illustrated by recent watershed simulations by Michael Dettinger, USGS, who studies the responses of detailed watershed models of rivers in the Sierra Nevada to global-change projections from GCMs.

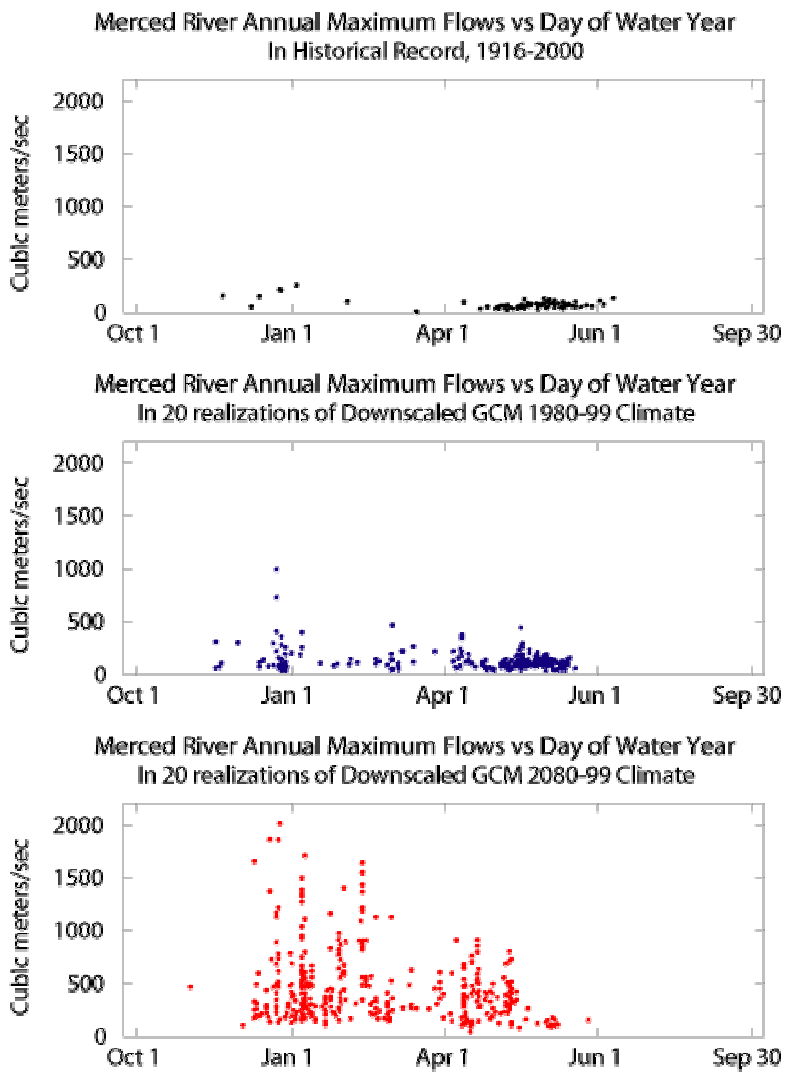
When a climate-change projection from the Parallel Climate Model at the National Center for Atmospheric Research is fed through watershed models of the Merced River above Yosemite Valley and the North Fork American River above North Fork Dam, many more days with high flows are simulated during the 21st Century than during the 20th Century. This particular climate-change projection yields several degrees C warming by the end of the 21st Century, but relatively small changes in precipitation amounts (on average). Thus the increases in high flows shown are responses to the warmer weather associated with the greenhouse climate.



These high flows reflect more rainfall runoff from these high-mountain basins, more rain-on-snow events, and more rapid melting of the snowpacks that do develop, in response to the warmer winter and spring climates projected.

Similarly, when climate-change scenarios derived (statistically) from the National Assessment's HadCM2 projections were used to force the same Merced River model, larger floods resulted. The figure below plots each year's maximum-daily floods according to its magnitude (on the vertical axis) and the day of year that each flood occurred (on the horizontal axis). The top panel plots floods in the 85-yr historical record at the Happy Isles gage in Yosemite Valley. The middle panel shows simulated floods when the watershed model is forced by 400 years of the GCM-simulated 1980-1999 climate (generated by statistical methods from a single GCM simulation).

The bottom panel shows floods when the watershed model is forced by 400 years of the GCM-simulated 2080-2099 climate. Clearly, there are many more, and much larger, winter floods (December through February) under the 2080-2099 climate than in observations and in the historical simulation. This increase in large winter floods is a response to both warmer winters and springs and much wetter winters (and winter storms) under this particular scenario. (The appearance that there are more winter storms in the historical simulation (middle panel) than in the historical record (top panel) is largely a function of the much larger number of years plotted in the middle panel (400 yrs in middle versus 85 in the top panel.)



Long-term simulations of changing flood regimes, like these, are difficult because reproducing the statistics of the most extreme flows with combinations of GCM and watershed models is still challenging. However, the changes suggested in these figures provide a sense of the large flood responses to warmer (and wetter) climates that may be expected under typical greenhouse scenarios. The "typical" size of annual maximum floods simulated under these scenarios increase (in the model combinations shown) by 3 to more than 5 times.

Lake Levels and Conditions

Changes in precipitation and runoff have important implications for lakes. During the 1987-1992 drought, Lake Tahoe experienced decreases in lake levels, causing reductions in water flows out of the lake to the Truckee River. Converseley, higher than normal precipitation later in the 1990s led to increased flows into Mono Lake, east of Yosemite National Park. The lake level and also the mix of fresh and salt water was impacted by the higher flows.

Droughts and floods, and resulting lake level fluctuations, are part of the natural variability in climate. Increased frequency and intensity of climate extremes would have important implications for lake systems. The water sector analysis notes that:

> While most research has focused on rivers and runoff, some studies have looked at the impacts of climate change on lakes. Lakes are known to be sensitive to a wide array of changes in climate conditions: variations in temperature, precipitation, humidity, and wind conditions can alter evaporation rates, the water balance of a basin, ice formation and melting, and chemical and biological regimes.[198] Closed (endorheic) lakes are extremely sensitive to the balance of inflows and evaporative losses. Even small changes in climate can produce large changes in lake levels and salinity.[199]

Groundwater

Groundwater is an important and valuable resource in California. On average, about a third of California's water supplies are derived from groundwater sources.[200] During dry years the percentage increases to two thirds. Groundwater in many basins in California is in overdraft condition, meaning more is being extracted over time than is being replenished. The Department of Water Resources estimates a statewide *increase* in groundwater overdraft of 160 tafy for the 1995 base year over the previous base year of 1990.[201] Total statewide overdraft in the 1995 base year is estimated at 1,460 taf.[202]

Surface and groundwater resources in California are inextricably linked. Both reductions in surface runoff (or flood surges which cannot be recharged) and increased temperatures leading to increased water use will potentially place added stress on groundwater resources. The potential impacts of climate change on groundwater resources in California have not been systematically examined. The National Water Sector Assessment reports that "Little work has been done on the

impacts of climate changes for specific groundwater basins, or for general groundwater recharge characteristics or water quality."[203]

Both the Hadley and Canadian model indicate significant *increases* in precipitation in Southern California. If this scenario plays out, there will be important opportunities for groundwater management. Recharge potential in Southern California groundwater basins is significant. Chino Basin, for example, estimates 1 – 2 million acre feet of potential storage capacity.

Sea Level Rise

The Intergovernmental Panel on Climate Change (IPCC) *Third Assessment Report* reports that the global mean sea level is projected to rise between 3.5 and 35 inches (9 cm to 88 cm) between 1990 and 2100.[204] The rate during the 20th century appears to have been around 0.2 meters, with a range of 0.1 to 0.25 meters.[205] Titus and Narayanan report the historic rate of increase in California over the past century has been about 0.5 inches per decade.[206] Roos notes that "this is consistent with the historical trend reported at the Golden Gate tide station, although it is possible that tectonic movement, or settlement, has influenced the stages there."[207] A study by Westerling suggests that the past rate of local sea-level rise might have been considerably higher than this estimate (e.g., 0.8 inches per decade, or 9 inches over the 110-year period).[208]

Relative levels will vary from place to place naturally as a function of geological activity. "Local levels also may rise because of human-induced land subsidence brought about by the removal of subsurface fluids (e.g., oil and groundwater). For example, a localized subsidence of nearly 30 feet was found in the Wilmington oil field in Long Beach during the 1940s and 1950s because of the oil pumped out but has been partially reversed by injections of seawater since the 1960s."[209] Relative sea level changes also result from changes in barometric pressure and when winds drive ocean water landward. "During El Niño events, the sea level can be elevated by as much as 1 foot for months or even a year."[210]

Francisco Bay and the Sacramento-San Joaquin River Delta[211]

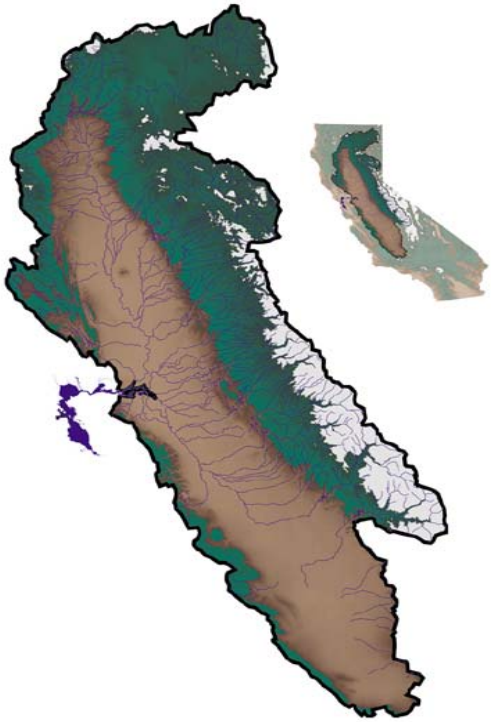
One of the first efforts to evaluate regional sea-level rise impacts on water-resource systems was done for the San Francisco Bay and the Sacramento-San Joaquin River delta in northern California by Williams.[212] This delta region is of critical importance for water supply for much of the state's population and is one of the few coastal estuaries in the western United States with significant remaining biological resources. Williams evaluated how sea-level rise would affect the location of the salt front and the stability of delta levees. These levees are vital for protecting transportation systems, agriculture, and homes in the region. Among the conclusions was that the fragile levees of the delta would fail at a higher rate, sediment movements would be changed, mudflats and salt marshes would experience more erosion, and ecosystem impacts could be substantial. For a one-meter sea level rise, the area and volume of this large west coast estuary could triple from 1,100 square kilometers to over 3,500 square kilometers if substandard levees were allowed to fail. Williams also concluded that the average salinity level could migrate roughly 15 kilometers upstream, leading to massive impacts on the state's water supply infrastructure. Other conclusions were that tidal marshes in parts of the San Francisco Bay where salt and freshwater ecosystems interact would be submerged by a one-meter sea-level rise.[213]

Sea level rise could cause "changes in salinity distribution in estuaries, increased risk of salt-water contamination at water-supply intakes, altered circulation patterns, increased pressure on coastal levee systems, and effects on biodiversity."[214] Two major water systems drawing water from the Sacramento-San Joaquin Delta may be impacted. Pumps extract water from the southern delta to supply the California Aqueduct (part of the State Water Project) and the Delta–Mendota Canal (part of the federal Central Valley Project). Water is pumped south to meet a portion of the uses in San Joaquin Valley agriculture and about a quarter of Southern California's municipal uses. A rise in sea level in the range projected would increase the salinity in the delta, particularly at times of low flow (summer-fall). Salinity affects both the drinking water and the habitat for native species, some of which are listed.

Sea-level rise may also affect groundwater aquifers by causing an increase in the intrusion of salt water into coastal aquifers, depending on the groundwater gradients and pumping rates. "While researchers have high confidence that sea-level rises will adversely affect coastal ecosystems and some groundwater aquifers, they have only medium confidence in the expected range of sea-level rise."[215]

San Francisco Bay/Delta Estuary
Salinity and Freshwater Inflow Forecast

Noah Knowles, Scripps Institute of Oceanography[216]



San Francisco Bay/Delta estuary (blue) and its watershed in California.

Background: San Francisco Bay and Its Watershed

California receives an annual average of nearly 250 cubic kilometers of freshwater in the form of rain and snow. Of this, about 40% ultimately becomes streamflow in the State's river network (California, 1979), which culminates at the Delta of the Sacramento and San Joaquin rivers at the head of San Francisco Bay. This freshwater supply is highly managed to ensure adequate supplies throughout the year. While most of this water originates in the northern third of California, a substantial portion is collected in artificial reservoirs during the rainy season for later conveyance to the areas of greatest demand in Central and Southern California. Controlled releases of stored freshwater are also used to flush saltwater from the Delta region and San Francisco Bay, protecting freshwater supply stations and maintaining the health of the Bay/Delta ecosystem. San Francisco Bay is the largest estuary on the west coast of the United States.

Freshwater Supply Variability

Variations in the timing and amount of the freshwater supply have significant social and economic impact in California. Excessive rainfall in a short period can overflow reservoirs and cause severe flooding, as in the storms of January, 1997. Conversely, insufficient total precipitation during a given rainy season can lead to freshwater shortages later in the year, potentially leading to water rationing, losses of agricultural and hydroelectric power commodities and other Statewide impacts. Low freshwater flow due to drought and excessive upstream diversions can lead to unnaturally high salinities in the Bay/Delta estuary, potentially contaminating freshwater supplies and adversely impacting the health of the estuarine ecosystem (e.g., Jassby et al, 1995). Interannual to interdecadal variations are also of strong significance. Multi-year events such as the drought of 1987-1992 have cumulative effects on economies and ecosystems. Also, a slow rise in winter temperatures since the 1940's has led to earlier snowmelt runoff (Dettinger and Cayan, 1995), effectively decreasing the natural storage in the Sierra on the interdecadal time scale.

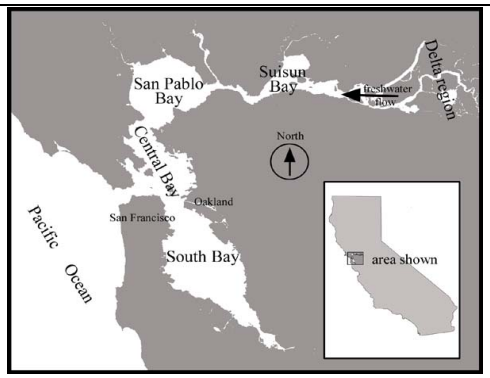
San Francisco Bay/ Delta Water Forecasts

Methods

Forecasts of Delta outflow, the estuary's freshwater supply, are statistical forecasts based on 51 years (WY1950-2000) of Delta flow (http://iep.water.ca.gov/dayflow/data/ and CDEC Delta outflow estimates) and Sierra snowpack (http://cdec.water.ca.gov/snow/bulletin120/) data. If the year being forecast is between WY1950 and WY2000, that year is excluded from the regression. The persistence predictions are based on a linear regression of future flow on current flow and snowpack conditions. To enhance the accuracy of the forecast, the ensemble is subdivided into "wet" and "dry" years, and the appropriate subset is used based on the relative wetness (compared to historical record) of the forecast year as of the forecast date.

The weather envelope is derived as the difference between observed flows and persistence forecasts for each year of the historical data set. This ensemble of "weather effects" is then added to the current year's persistence forecasts to yield the "weather probability distribution" shown in red. In the flow and salinity forecasts, only the estimates of the 10th and 90th percentile weather effects are shown for clarity.

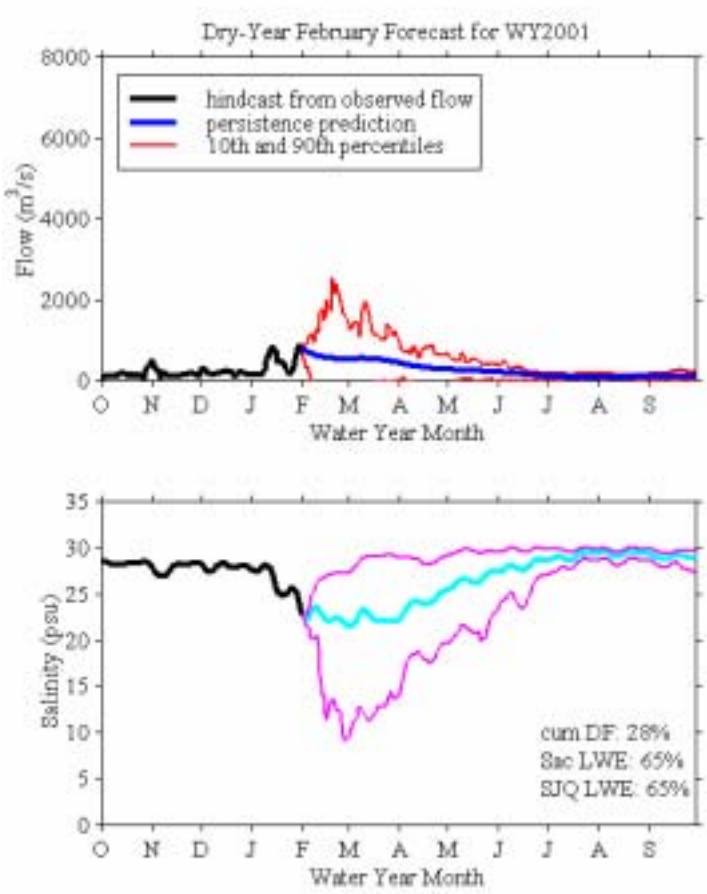
The salinity forecasts were generated by using each member of the flow forecast ensemble as input to the U-P Water Quality model (Uncles and Peterson, 1996). This model has been shown to accurately reproduce Baywide salinity variability at time scale of weeks to decades (Knowles, 1997, 1998). Forecasts have been generated for San Pablo Bay (see below), the region of greatest salinity variability in the estuary. Forecasts are easily developed for any other location in the estuary. The forecast for WY2001 is discussed next.



Location of major landmarks and sub-estuaries in the Bay/Delta estuary.
San Pablo Bay is in the northwest corner of the estuary.

Forecasts

Shown to the right is the series of 4 monthly forecasts generated for WY2001. As of May 8, this year ranked 10th driest among the years WY1950-2000. Similar ranks held for all prediction months. All four forecasts are therefore based on regressions of conditions in the driest years of the record (years with total flow below the median).



Note the gradual narrowing of the forecast distribution with time, both within each forecast, and as the forecast month progresses through the series. On average most anomalous precipitation occurs by April, and once snow is on the ground, the snowmelt anomalies are strongly predictable. This means that after April, the forecast distribution typically narrows considerably, as is the case here.

The low precipitation this year means that San Pablo Bay salinity will stay near dry season levels all year, although in February, there was still a strong possibility of low salinities. By March, the forecast shows little likelihood of a significant freshening, and by April, a saline year is virtually guaranteed. It is instructive to compare this year's forecast with those of other recent water years. Analogous forecasts for WY1997-2000 are accessible

Direct Effects on Ecosystems

Water is critical to ecosystems in several ways. Seasonal patterns of precipitation and runoff, along with timing, temperature, and quality, are important factors for species and for ecosystem functions.

The Water Sector Assessment notes that, [217]

> The health and dynamics of ecosystems are fundamentally dependent on a wide range of climate-sensitive factors, including the timing of water availability, overall water quantity, quality, and temperature. All of these factors may be altered in a changed climate. Humans, in turn, are dependent upon ecosystem processes to supply essential goods and services: for example, primary productivity and inputs from watersheds support food webs yielding fish for commercial and recreational purposes; decomposition and biological uptake purify water by removing organic materials and nutrients. Freshwater systems are rich in biological diversity, and a large part of the fauna is under threat of extinction.[218] A changing climate may intensify these threats in many ways, such as by accelerating the spread of exotic species and further fragmenting populations.[219]

Previous assessments "have established a wide range of possible direct effects, including changes in lake and stream temperatures, lake levels, mixing regimes, water residence times, water clarity, thermocline depth and productivity, invasions of exotic species, fire frequency, permafrost melting, altered nutrient exchanges, food web structure, and more.[220] These impacts could lead to a wide range of serious adverse impacts on ecosystems, with changes in vegetation patterns, possible extinction of endemic fish species already close to their thermal limits, declining area of wetlands, precipitating reductions in waterfowl populations, concerns about stream health, and major habitat loss." [221]

The report also notes[222] that while "some climate scenarios can produce conditions that might reduce stresses on certain ecosystems, experience with ecosystem dynamics strongly suggests that perturbing ecosystems in any direction away from the conditions under which they developed and thrive will have adverse impacts on the health of that system.[223] One likely consequence of a warmer climate is increasing fragmentation of cold-water fish habitats in headwaters and potential shifts in the competitive dominance of salmonid species."[224]

Further discussion of ecosystem impacts appears later in this assessment.

Medium-Range Forecasts

Statistical Evaluation of Medium-Range Weather Forecasting Models

California Applications Center/Scripps Institution of Oceanography [225]

Climate and weather wield great influence over human activities, many of which depend heavily on the accuracy of weather forecasts -- farmers rely on them for planning how to manage crops, utility companies for anticipating energy demand, water managers for planning reservoir operation to conserve scarce water, and firefighters for estimating fire risks, to name but a few.

The longer the lead time of such predictions, the more useful they are. But weather and the atmospheric general circulation models that researchers use to approximate it are highly sensitive to even small changes in incompletely known initial conditions and other boundary influences. This causes the reliability of the average forecast to deteriorate markedly within just a week or two, and so researchers are continually seeking ways to extend the viable range of weather forecasts.

In general, researchers pursue two basic approaches to improving forecasts. One is to directly improve the accuracy of the model representation of weather processes, initial conditions, and boundary conditions, as well as to dedicate

increased computational resources in hopes of extending the length of time before model and real-world weather conditions diverge.

The second way of improving forecasts is statistical. This is the approach being followed in the Historical Medium Range Forecast (MRF) Ensemble Project by Dan Cayan, Director of the Climate Research Division at the Scripps Institution of Oceanography (SIO) and colleagues at the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP) and the NOAA Climate Diagnostics Center. "The goal of our research is to evaluate the reliability of medium-range forecast modeling using statistical measures to determine in a quantitative way how good the forecasts are out to 15 days, or sometimes 30 days. How reliable are the predictions? Are there systematic biases to the models? And do the statistics change with the prevailing climate -- for example, are the predictions better or worse during an El Niño than in ordinary years?" said Cayan.
Cayan's group is using is the NCEP Global Spectral Model, a standard modern model with 28 vertical levels and horizontal resolution of T62 or about 1.8 degrees of latitude. The model physics include a radiation code, simplified diffusive planetary boundary layer, gravity wave drag, clouds, and other features. This improved model also includes parameterization for soil moisture, vegetation, and snow.

To evaluate statistically how good the model forecasts are, the researchers run the model for past years, "predicting" archived weather conditions. That is, they run the model for each day in a previous year and see how well it predicts the archived weather records on subsequent days, out to 15 or 30 days later. Because weather models are continually being improved, the researchers use a standard weather model that they have "frozen" in a recent version so that they are always comparing predictions from the same model. In this way, Cayan and colleagues are producing a comprehensive new data set of forecasts, which has numerous uses at both the global and regional scales. "In effect, this data set is going to provide us with the 'climatology' of medium range weather forecasts," said Cayan.
Applications from Fire and Water to Health

In addition to the role that the new forecast data set can play in improving global weather models, Cayan and colleagues are vigorously applying their research to tangible problems close to home through the California Applications Program or CAP, providing guidance for the study of weather-related influences on human health conditions, water and energy predictions, and fire season severity assessments, among others. Cayan explains that "our studies give researchers an important tool to shed light on a wide range of specific problems."
Many sectors of society depend on routine weather predictions, but the reliability of these forecasts becomes especially crucial in the case of extreme weather events. In studying storm predictions for California -- an example of downscaling global weather forecasts to a more focused and useful regional scale -- Cayan works closely with Michael Dettinger, a US Geological Survey research hydrologist and also a member of the Climate Research Division at SIO, who uses the medium range forecast data set as input for hydrology models, producing predictions of streamflow runoff for California.

In the 1997 Northern California New Year's flood, for example, an intense, three-day storm produced by the "pineapple express" picked up tropical moisture in the jet stream and swept it to California, where it did billions of dollars in damage and forced the evacuation of tens of thousands of people from flooding rivers. "This was one of the largest runoff events ever recorded at places like Yosemite, with boulders the size of cars rolling down the Merced River. We are very interested in determining how far ahead such events can be predicted," said Cayan. In a promising development, it turns out that indications of this major precipitation event can be seen in runs of the forecast model on weather data even a week prior to the event, and perhaps beyond (Figures 1 and 2).

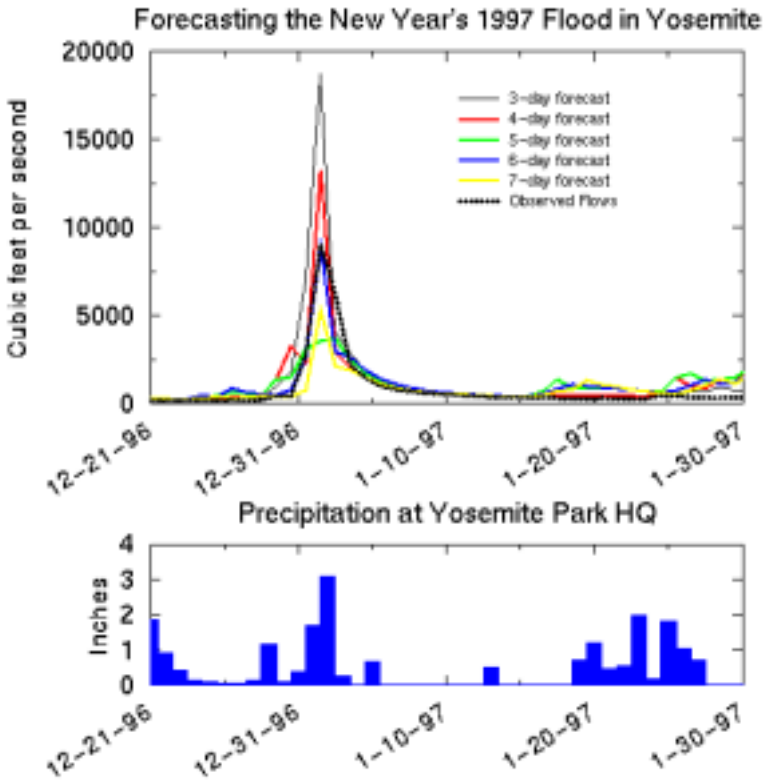


Figure 1: Medium-range weather forecasts predict this major precipitation event more than one week in advance. The figure shows the amount of flow in the American River based on forecasts from 3 to 7 days in advance. For comparison, the lower panel shows the observed precipitation recorded at Yosemite Park Headquarters.

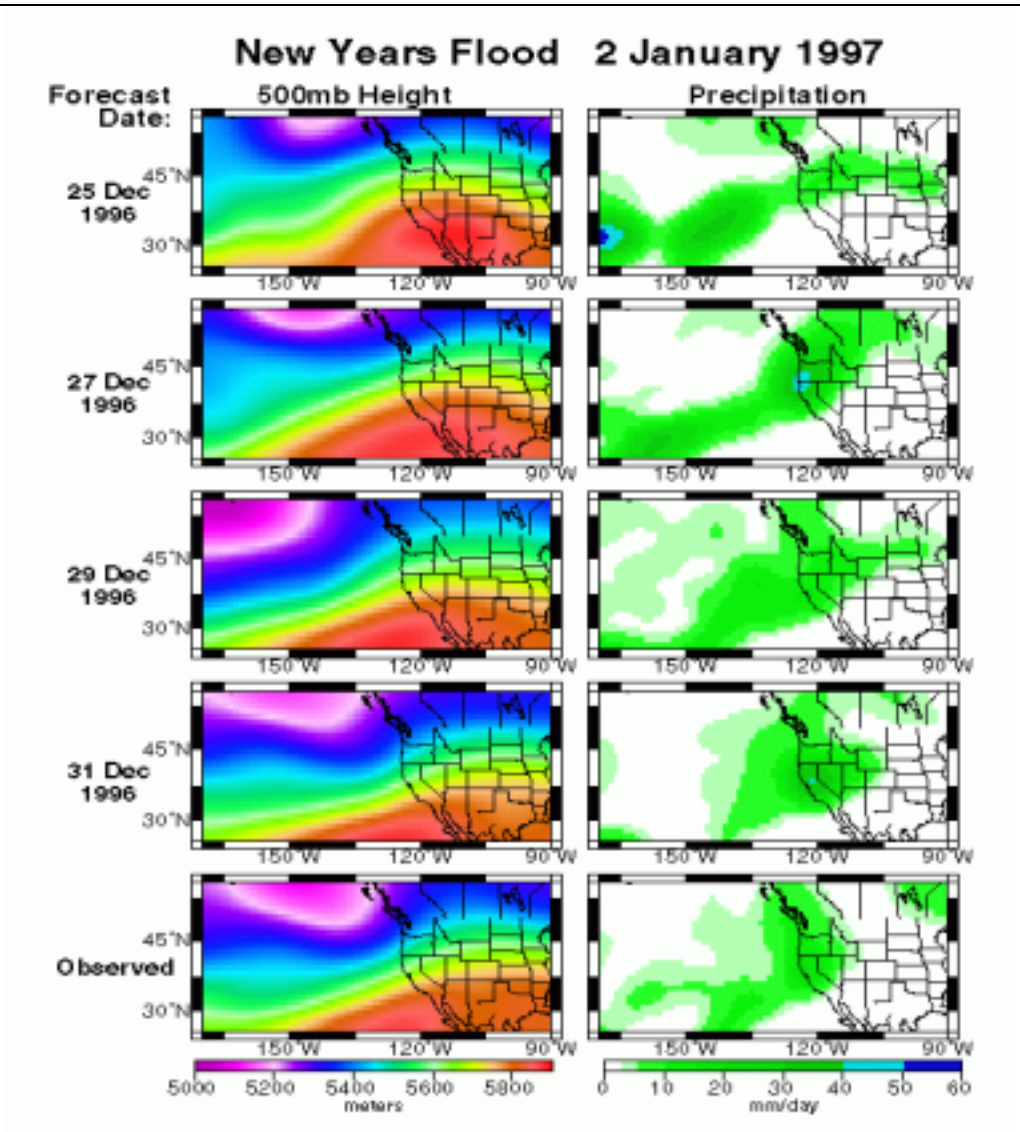


Figure 2: Medium-range weather forecasts showing the 500 mb height and total precipitation before the major January 2 precipitation event.

"Although our immediate applications are aimed at the local region of California, our new forecast data set will have global usefulness," said Cayan. This is because weather forecasts such as those in the data set are always produced initially at a global scale since weather models must necessarily include all the interconnected parts that make up the complete global weather and climate system. Thus, researchers in Florida or Montana, for example, could use these same forecasts to help improve their ability to predict fire conditions there, a serious problem in recent years.
Statistics: Zeroing in on Forecast Effectiveness

The basic approach that Cayan and colleagues are using is to run the NCEP Global Spectral Model for past periods, using the same methods used for present-day operational forecasts, and then to compare the forecasts with archived weather records. In addition to examining the predictability of the events, the researchers are studying how reliable the predictions are by performing multiple forecasts, generating sets or ensembles of ten forecasts for each day that are entirely similar except for initial conditions. In this way, they develop maximum likelihood forecasts by averaging out the presumably noisy differences between ensemble members, and estimate the potential forecast error by measuring the spread between the individual forecast members.

"These ensembles let us characterize model biases and year-to-year variations in prediction skill in terms of ensemble-mean behaviors and ensemble spreading, allowing investigation of bias, skill, and reliability," said Cayan. This approach also provides the likely range of near-future weather conditions inherent in the forecast uncertainties. But how do the researchers create ten forecasts from one set of initial conditions? Using a method called "breeding," they identify the largest differences between the observed or initial conditions and the model forecast, which are then used to modify the model initial conditions.

"What we're looking at is the 'week two' time frame in forecasting, which is not well explored yet. People generally don't tend to believe forecasts beyond five days or so, partly because there hasn't been a lot of research on how to evaluate and make the best use of these predictions. It's expected that a hybrid approach will ultimately be best, where we combine physical weather models with statistical approaches like ours that can help 'tune' the forecasts by incorporating corrections for such things as biases in the models, which can also vary with conditions like El Niño," said Cayan.

"Our long-range goal is to make ten ensemble runs per day from 1970 to the present, but in order to put our efforts where the immediate payoffs will be biggest, we're focusing on the all-important ENSO episodes -- both El Niños and La Niñas -- and soon we'll be able to quantify and predict forecast skills, before the fact, during these climate conditions that bring California some of its greatest climate-driven threats and opportunities," said Cayan. As they investigate how predicable storm and inter-storm conditions are during the various phases of ENSO episodes, the researchers will also determine whether short-term predictability during the 1997-2000 ENSO is typical of previous ENSO episodes from the 1980s.

Computing the Weather

All global weather forecasting models are very computationally intensive, and in Cayan's research, in order to make valid forecast skill assessments that apply across the whole range of climate conditions that can occur, large numbers of daily forecasts spanning many years must be made and compared to their real-world outcomes. Looking ahead, modelers would also like to increase the resolution from the current 100 km or so to 10 km, as this will lead to more accurate simulations of weather and climate, especially in topographically rough regions such as California and the West. However, this will require even greater computing power, and so this research will continue to require the most powerful computational resources available.

In addition to requiring substantial computing power, the resulting data sets are significant in size, and the High Performance Storage System (HPSS) facility at SDSC is needed to store them. Because of the value of the data sets to many other researchers, Cayan is planning to make them available on the Web. Regarding computing platforms, the "frozen" NCEP Global Spectral Model being used currently runs on the Cray T90 vector machine, and these models are in the process of migrating to parallel codes.

"The combination of powerful computational resources, large data storage capability in the HPSS, and high-performance computing experts like Phil Papadopoulos and Giri Chukkapali, make SDSC an invaluable resource for this research," said Cayan.

Beyond the immediate applications of the CAP program, the forecast data sets may well have uses in hybrid approaches to predicting the weather, which combine numerical models with statistical approaches that complement and extract the maximum information from model forecasts. At the same time, they can also provide guidance about which aspects of the computational models to improve.

"Many researchers are now realizing that you need forecast data sets as much as observational data sets, and this will be a continuing research saga," said Cayan.

More information about the Historical Medium Range Forecast (MRF) Ensemble Project is at http://meteora.ucsd.edu/cap/hindcast.html. More information about the 1997 New Year's flood is at http://meteora.ucsd.edu/cap/flood_newyears.html. The CAP Web site can be found at: http://meteora.ucsd.edu/cap/. More information about SDSC and its computational resources is at www.sdsc.edu/. --PT

Using Science for Adaptive Management: CALFED

The following is a set of concise and highly relevant contributions to the CALFED planning process. They focus on impacts of climate change and variability to the San Francisco Bay-Delta.

Climate Variability and CALFED

The following summaries were written by:
Dan Cayan, SIO, with
Kelly Redmond, DRI, and
Mike Dettinger, USGS
As a CAP/PACLIM Contribution to the First CALFED Science Conference
CALFED Science Conference, Oct 3, 2000
http://meteora.ucsd.edu/paclim/calfed.html

Conveners' overview

Climate variability and its effects are the biggest single natural environmental driver of the Bay-Delta system. Observed past variations in climate on historical (past 150 years) and paleo- (over the past several hundred years) time scales, and ongoing changes in climate, provide clear evidence that climate variability needs to be addressed as a science topic with important policy implications as the CALFED program proceeds. Improved understanding of the range and mechanisms of climate variability, and of the specific context of CALFED actions and decisions within this variability, is essential if management strategies are to be correctly planned and evaluated.

Monitoring of the Climatic Context of CALFED: Opportunities and Options

Kelly Redmond, Western Regional Climate Center, Desert Research Institute

Monitoring the physical manifestations of climate and weather that affect the delta and its biological inhabitants must be carried out and sustained if CALFED actions are to be understood in their proper contexts. The atmosphere, the watershed and the coastal ocean all contain a rich spectrum of spatial and temporal structure, much of which is incorporated into the variability of the Bay/Delta. Several observation networks, many of which were not designed for climate purposes, are necessary to provide this spatial and temporal information. The integration of varied existing data sets and data collection programs (scattered throughout different agencies and groups) is complex and requires planning and support. Methods for more easily and efficiently accessing data archives are needed. Acquisition, storage, distribution, display, and manipulation of archived values is currently available, but to varying degrees of success and effectiveness; better infrastructure would benefit a spectrum of scientists and managers.

Sierra Nevada Snowpack--The Crucial Source of Fresh-water to the San Francisco Bay

Frank Gehrke , California Cooperative Snow Surveys, California
Dan Cayan, Scripps Institution of Oceanography / U.S. Geological Survey
Maury Roos, California Dept of Water Resources

The amount of water accumulated in the Sierra Nevada is the major contributor to fresh water feeding the San Francisco Bay/Delta. Snow accumulation in the high Sierra usually reaches its apex around late March or early April, but from year to year, the timing changes by weeks and the maximum accumulation often varies from its long term average by +/-50%. A substantial fraction of the watershed's snow covered area lies in the moderate elevation

zone that would be vulnerable to increases in temperature, so global climate change could produce a marked decrease in the natural storage that is provided by the seasonal Sierra snowpack. A critical observational program is the California Cooperative Snow Surveys, which maintains a network of over 300 human-observed snow courses and over 100 automated recording snow sensors. A comprehensive effort to gage the snow accumulation in California by measuring the depth and water content of the snow in a set of regularly monitored snow courses was begun in 1929, provoked by the threat of drought and the need to survey the volume of runoff that could be expected from the snowpack. Continuously recording snow sensors have been introduced more recently, generally beginning in about 1980. Very large Sierra snow accumulation years such as 1952 and 1983, and very poor snow accumulation years such as 1977 and 1988 were associated with persistent, large scale climate anomalies.

The Hydroclimatology of California Floods and Droughts

Daniel Cayan, Scripps Institute of Oceanography and USGS
Maury Roos, California Dept of Water Resources

Floods and droughts are an important part of the climate of the Sacramento and San Joaquin drainage basins. Larger scale Pacific basin atmospheric circulation systems are always involved, but unfortunately, there is no one unique pattern that causes floods and especially droughts; the 1987-1992 drought was marked by several different large scale climate conditions, including both El Nino and La Nina. Large floods have gotten larger in the last 3-4 decades in some of the major Sierra Nevada streams. Proxy high resolution paleoclimate data (tree rings, sediments, etc) and numerical models are two important vehicles to extend the rather short instrumental record of drought and floods. Under climate change, we could experience higher winter floods due to more rainfall runoff and rapid snowmelt. The summer dry regime could become more intense if streamflows recede more quickly.

Sierra Nevada Runoff into San Francisco Bay Why Has it Come Earlier Recently?

Michael Dettinger, USGS

"Roos ratios" (the fraction of water-year streamflow occurring each year during the April-July snowmelt period) have declined by ~10% since the 1950's in both the northern and south-central Sierra Nevada. This change was illustrated visual and statistical inspection of the Roos-ratio time series for trends, as well as by comparisons of long-term averages of hydrographs before and after about 1965. Winter and spring temperatures have increased in the Sierra Nevada since the 1940s. This warming has been large enough overall to explain the streamflow-timing trends, if we assume that the observed year-to-year streamflow-timing sensitivity to temperatures is also applicable to the long-term trends. This point is demonstrated by regression modeling of streamflow responses to seasonal temperatures during trendy and non-trendy periods. The temperature trends are associated with corresponding trends in winter- and springtime Pacific/North American-sector atmospheric circulations. These atmospheric trends have bent winds (and storm tracks) to be progressively more southerly as they reach the West Coast. This more southerly wind direction has been statistically sufficient to explain the observed warming in California. The changing atmospheric circulations, in turn, have been associated with corresponding North Pacific sea-surface temperature (SST) trends; these SST trends serve to confirm that the atmospheric-circulation trends are real and the air-sea interactions that they imply may eventually help to explain those circulation trends.

Meanwhile, it has recently been discovered that some of this long-term streamflow-timing trend has been masked in recent decades by the decadal variation of the North Pacific climate called (variously) the Pacific Decadal Oscillation (PDO) or the North Pacific Oscillation. This climate oscillation is very similar to (and may be a large part of) SST and atmospheric-circulation trends discussed previously. The primary distinction may well be that this oscillation has been observed to be reversible (i.e., it does not imply monotonic climate trends). For the Sierra Nevada, the recent states of the PDO, in the decades immediately before and after 1976, have resulted in northward and then, more recently, southward displacements of the North Pacific storm tracks arriving at the West Coast. The recent southward displacement of the storm tracks associated with the PDO has led to subtle changes in the distribution of precipitation in the Sierra Nevada. The resulting overall discharges from the northern and south-central Sierra Nevada have not changed much, but the ratio of the discharges from the two regions has changed

markedly. Proportionally more precipitation has fallen in the south-central Sierra (compared to the northern Sierra) since 1976; thus proportionally more streamflow has been generated in south-central Sierra. The south-central Sierran rivers however drain much higher mountain basins and thus hold the winter precipitation until much later in the year than do the northern basins. Consequently, the redistribution of precipitation and streamflow into the south-central rivers has led to later Sierra-total streamflows.

The timing of freshwater inflows to the Bay/Delta system is a critical determinant of overall Bay/Delta salinity and health. Thus changes in the timing of generation of streamflow in the Sierra Nevada can have important consequences to CALFED plans and actions. Trends towards earlier runoff imply a redistribution of streamflow from the springtime category of "water resource" into the wintertime category of "flood hazard". If the trends continue unchecked or unrecognized, the ability of CALFED actions to control Bay/Delta salinities while meeting California's flood-management and resource-management needs may be hampered. Notably, the climatic patterns associated with the observed changes in streamflow timing are of a global-scale form that has been called the COWL pattern (Cold Oceans-Warm Lands). The COWL pattern is an important part of both natural climate variability (in which case it reverses itself from time to time) and simulations of greenhouse warming (in which case it does not). Thus, whether the observed streamflow-timing trends in California will reverse themselves anytime soon is an unsettled issue.

Ocean Climate and Variability: Patterns and Implications

Francis Schwing, Pacific Fisheries Environmental Laboratory, NMFS

Coastal currents, upwelling, and ocean temperatures along the coast of California are strongly influenced by the behavior of the overlying atmosphere, and vice versa, and also vary seasonally. These affect migratory patterns, nutrient availability, predator-prey relations, ocean habitat, phytoplankton, and estuarine conditions experienced by ocean dwelling and anadromous fish. Timing of the spring transition, the location and strength of the subtropical high, the strength and direction and timing of alongshore winds, and fog patterns are among the climate elements directly and indirectly affecting aquatic life which show long term variations during this century. It is evident that there are ties to large scale climate structure, but there are also numerous subtleties in the interaction.

Natural and Human Influences on Freshwater Flows and Salinity in the San Francisco Bay/Delta Estuary and Watershed

Noah Knowles(1), Dan Cayan(1,2), Mike Dettinger(2,1), Dave Peterson(2)
1 Scripps Institution of Oceanography
2 U.S. Geological Survey

The San Francisco Bay-Delta estuary has been the subject of intense scientific scrutiny in recent decades, stimulated largely by concerns about destruction of natural habitat, contamination of the rivers and estuary, and declines in aquatic species populations. Like all estuaries, behavior of the Bay-Delta is linked to the coastal ocean and to the inland rivers, resulting in high variability at many scales. Also, the estuary has undergone extensive human development over the past 150 years, as has its upstream watershed. Current attempts to understand and restore the Bay-Delta's valuable ecosystems are complicated by both natural and human effects on freshwater inflows. In particular, long-term changes in estuarine conditions complicate attempts to understand the estuary's behavior on the basis of short-term studies. Examining long-term estuarine changes and their causes provides a more complete picture of the estuary and its ever-changing climatic context.

One aspect of the estuary's behavior that has undergone interdecadal changes is the timing of the annual salinity and freshwater inflow cycles. The low-pass filtered (10-year cutoff) timing of the annual cycles of both salinity and inflows shows a trend toward earlier cycles from the 1930's through about 1970, with a subsequent abatement of this trend reaching into the 1990's. A breakdown of the changes in freshwater inflow timing into natural (unimpaired) and managed components reveals that both contribute to this pattern, though natural variability dominates the trend toward earlier runoff before 1970 while management effects dominate the trend abatement.

From the late 40's through the mid-70's, the management effect increased in magnitude, coinciding with the period of development of California's massive water projects. After the mid-70's , the management effect subsided considerably, possibly due to management changes as well as to the extended drought beginning in 1987. Between the mid-30's and the early 70's, the filtered unimpaired flow signal shifted earlier by about 15 days. Subsequently, this steady trend broke down, replaced by shorter fluctuations. Several natural forcing factors have been identified which contributed to the timing signal. The first of these is a long-term trend toward earlier runoff of Sierran snowmelt, originally identified by Maury Roos (Roos 1987). This trend has since been associated with a spring warming trend (Dettinger and Cayan 1995). Two additional factors have been identified that affect the timing of unimpaired watershed outflows: the north-south distribution of precipitation and the timing of precipitation. Climate signals such as ENSO and NPO affect the relative distribution of precipitation in the northern and southern halves of the Bay-Delta watershed (Dettinger 2000). This, in turn, affects the timing of watershed outflow, since the two halves have very distinct hydrological behavior and annual hydrograph timing. At the interdecadal scale, NPO forcing is the dominant climate influence in this watershed. Different NPO "phases" correspond to different ratios of northern to southern precipitation and unimpaired flows, reflecting the shift of precipitation distribution associated with this climate phenomenon. This results in a contribution to unimpaired flow timing that oscillates at the multi-decadal scale, with high NPO index associated with later flows and vice-versa.

The remaining factor that contributes strongly to long-term changes in unimpaired flow timing is the timing of precipitation, particularly in the rainfall-dominated Sacramento basin (Figure 2, bottom plot). While the causes of this variability are not known, there is no apparent association with NPO, so this must be considered a separate effect.

In summary, long-term changes in the timing of the annual salinity and inflow cycles in the Bay-Delta estuary are a result of both natural and managed effects. Natural variability is influenced at the interdecadal scale by three main factors: changes in precipitation timing, a long-term warming trend causing earlier runoff, and NPO-related timing shifts. It is particularly interesting to note that since 1977, NPO has been in a "phase" which has tended to counteract the effects of the long-term warming trend. Preliminary evidence suggests that NPO may have shifted phase in the last few years. If this is true, and if the warming trend continues, it is possible that a tendency for very early runoff may characterize the next few decades.

Behavioral Response to Climate Change and the Decline of Striped Bass in the San Francisco Estuary: Importance of Estuarine-Ocean Ecosystem Linkages

William A. Bennett, John Muir Institute of the Environment, UC Davis and
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The effects of climate change can be difficult to distinguish from human interventions acting on fish populations within the San Francisco Estuary. We present analyses suggesting the decline in striped bass is related to a period of frequent El Niños and a concurrent shift in the atmosphere-ocean climate (Pacific Interdecadal Oscillation, PDO) beginning in 1976-1977. Previously, the decline of striped bass has been attributed to impacts on larval and juvenile fish due to exporting fresh water, and recently to density dependence during the pre-adult stage. We show that older striped bass (age 6+ years) migrated more frequently to the warmer Pacific Ocean during multiple El Niño events and the PDO shift, reverting to the behavior of native striped bass populations in Atlantic estuaries. Time series analyses of adult abundance estimates, sport-fishing records, and ocean environmental variables indicate significant associations between a step-like decline in adult abundance in the estuary, and higher occurrence of older adults in the ocean, with a step-like increase in ocean temperatures and relaxation of upwelling. Rises in ocean temperature are also correlated with rates of decline of adult cohorts in the estuary. In addition, reports in the sport-fishing media and by researchers indicate the sudden appearance of substantial numbers of adult striped bass in the Los Angeles area during the recent La Niña in 1997-1998. These results implicate changing ocean conditions as an important factor affecting the residency, and thus apparent mortality of older striped bass in the estuary. Frequent migration from the estuary combined with density dependent survival of pre-adults may be precluding restoration of the

estuarine population. This example illustrates the importance of estuarine-ocean linkages and the challenges posed by climate change for management.

Tree-ring Reconstruction of San Francisco Bay Salinity: 1604-1997

David W. Stahle, University of Arkansas

Blue oak (Quercus douglasii) tree-ring chronologies from California are highly correlated with winter-spring precipitation, Sacramento-San Joaquin streamflow, and with salinity in San Francisco Bay. A blue oak reconstruction of salinity explains 81% of the interannual variability of seasonalized surface salinity measured at the Golden Gate from 1922-1952 (Fort Point), a period preceding the massive diversion of freshwater from the Sacramento-San Joaquin system. The reconstruction indicates that the post-diversion salinity extremes witnessed in San Francisco Bay after 1952 have been unprecedented over the past 400 years, particularly during the record California droughts of 1976-1977 and 1987-1992. These recent extremes and the 2.52% increase in average January-July salinity measured at Fort Point from 1953-1994 appear to largely reflect the anthropogenic appropriation of Sacramento-San Joaquin streamflow.

Summary and Conclusions

CALFED Climate Issues: CALFED is a bold and audacious attempt to exercise adaptive management on a large scale and in a complex sociopolitical environment. To properly evaluate the effectiveness of intervention actions, after observing particular outcomes, we must possess sufficient understanding of system behavior to estimate what would have happened naturally, without intervention. What outcomes were more plausible or possible in the absence of intervention?

The flow of fresh water into and through the Delta is the major driver of much of the non-tidal variability of salinity and other physical and biological properties in San Francisco Bay. The factors which link this flow to climate behavior at all space and time scales, ranging up to the size of the Pacific Basin or even the globe, must be better understood. The degree of predictability of each of these factors must be established.

During times of climate extremes (drought and wet spells), impacts of climate variability on fresh water flow, salinity and presumably other Bay/Delta properties is so large that it overwhelms any counterbalancing influences of human management.

Routine and systematic monitoring of physical and biological variables is vital. The spatial domain relevant to the Bay-Delta area extends to the upper headwaters of the Sacramento / San Joaquin and also includes near-shore ocean conditions. The region exhibits long-term trends in the timing of snowmelt (toward earlier in spring) that need to be placed in wider perspective. The prospect for global climate changes to affect this area highlights the need to be able to detect subtle long-term trends.

In the past fifty years the well-studied flood regime on the American River has undergone a dramatic change toward more frequent very large floods. We have no idea why this has occurred, and do not know whether the next fifty years will relax back to the first half of the 20th Century. Changes of this magnitude in the flood hydrology have enormous implications for the design and interpretation of adaptive management experiments.

Considerable experience with similar (though smaller) programs and projects shows that the vast array of science efforts now underway will request, expect, and eventually demand access to the wide variety of climatic, hydrologic, biologic and physical data that exist. Existing systems for the provision of such information should be augmented to handle the expected demand for such information from the research community and others. Ease of access and interpretation are important factors to consider.

Several long term unexplained trends in temperature and precipitation have been noted for the Calfed region. These may be true monotonic trends, or they may result from slow oscillations between different climatic regimes. In many of the relatively short records available, regime shifts from one 20-30 year span to the next may masquerade as "trends" because they have not been observed long enough. For example, the Pacific Decadal Oscillation can and apparently does produce such behavior, and may have also recently (late 1990s) shifted back to a prior state. Ocean currents very likely respond to such climate shifts on the scale of several decades.

In addition, the variability of climate has increased dramatically since the 1970s. During this short period the state has experienced the wettest and driest individual years in its long history, and the wettest and driest multi-year averages. Each of these, wet and dry, have occurred in the presence of each of El Nino, No Nino, and La Nina, so obviously there is much to be learned.

Coastal Pacific sea Level responds to multi-scale climate variations and must be understood and predicted; in some cases, sea level rises sharply in response to the same storms that produce excessive precipitation and runoff, so the two phenomena should not be treated separately in planning for high sea level events or episodes. On top of this, the rate of sea level rise, currently about 15cm/century along the California coast, is expected to accelerate under global warming scenarios. This must be considered in long range planning.

The reasons why central California experiences floods and droughts are not clearly understood, or well predicted. There appear to be differences in the character of floods between the Coast Range and the Sierra Nevada that relate to whether El Nino or La Nina is present. Other factors also must play a role, because floods and droughts occur during periods with and without anomalous tropical Pacific conditions.

We do not have an adequate understanding of the climatic context of the 20th Century. How representative is the period of historical and/or instrumental records of the past millennium? Evidence from sequoias suggests that the 20th Century may have been the wettest in two thousand years. How robust is this conclusion? What are the implications? If true, will this continue? California is relatively blessed with an abundant and widely distributed supply of excellent and even unique natural rainfall recorders, in tree rings and other proxy records. These recordings provide invaluable and detailed information about both spatial and temporal variations in past climates for several hundred individual years, and a diligent and aggressive effort should be under way to learn the climatic lessons these trees have for us. Thus, the ability to reconstruct past interannual variability of moisture and other climatic measures from tree rings and other proxies is invaluable and should be pursued with more extensive collections and diagnostics.

Summary

California's water systems are complex, and there are a number of potential impacts of climate change and variability for water supply, quality, and use. Some of the possible futures identified by scientific research and computer modeling are extremely serious.

It is clear that *pattern changes* in precipitation and runoff could be critically important, even if statistical averages of precipitation remain constant. Some of the projections, such as those that identify a possible increase in precipitation in Southern California, could be good news for some. On the other hand, increases in temperature may lead to drier conditions, increased demands for water, and less storage of water in the form of snow in the mountains.

The water sector report includes the following "key messages" for water managers and others for water managers, planners, and interested members of the public:

Key Messages [226]

Climate is not static and assumptions made about the future based on the climate of the past may be inappropriate. Assumptions about the probability, frequency, and severity of extreme events used for planning should be carefully re-evaluated.

Climate changes will be imposed on top of current and future non-climate stresses. In some cases, these changes will be larger than those expected from population growth, land-use changes, economic growth, and other non-climate factors.

Certain threshold events may become more probable and non-linear changes and surprises should be anticipated, even if they cannot be predicted.

The time lags between identifying the nature of the problems, understanding them, prescribing remedies, and implementing them are long. Waiting for relative certainty about the nature of climate change before taking actions to reduce climate-change related risks may prove far more costly than taking certain pro-active management and planning steps now. Methods must be used that explicitly incorporate uncertainty into the decision process.

While some kinds of actions should be taken now, expensive and long-lived new infrastructure should be postponed until adequate information on future climate is available. If postponement is not possible, a wider range of climate variability than provided by the historical record should be factored into infrastructure design.

Water managers, including the California Department of Water Resources, are taking the issue of climate change seriously. A chapter in the next state water plan will be devoted to the issue.

The Next part of this section outlines coping and adaptation strategies as well as research priorities.

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[7] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994. (Figures from Vol.1, Table 1-1, p.5, unless otherwise noted.) Bulletin 160-98 figures are similar to Bulletin 160-93, with basic precipitation numbers unchanged. Due to changes in methodology used in Bulletin 160-98, data from Bulletin 160-93 is presented here.

[8] "Non-developed" uses are evaporation, evapotranspiration from native plants, and percolation.

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[10] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Vol.1, p.51.

[11] "Total" figures for both 1960 and 1990 from figure 3-1. The 85 mafy figure includes groundwater extractions including overdraft of 15 mafy and surface at 70 mafy.

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[35] California Department of Water Resources, 1994, *California Water Plan Update*, Bulletin 160-93, Vol. 1, pp.159-184. Projection for 2020 on p.181, Table 7-13. (See Figure 7-1 on page 159 for a comparison of Bulletin 160 projections.)

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[42] DWR includes extensive discussion of the changes in the agricultural sector and in its water use in Bulletin 160-93.

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[44] Wilkinson, Robert C., 2000. Analysis for California Department of Water Resources State Water Plan Process, Bulletin 160-03. Sources of figures by report year:

1957 California Department of Water Resources, Bulletin 3, *The California Water Plan*, May 1957, p.14, Table 3.
1966 California Department of Water Resources, Bulletin 160-66, *Implementation of the California Water Plan*, March 1966, p.53, Table 6.
1970 California Department of Water Resources, Bulletin 160-70, *Water for California*, December 1970, p.47, Table 4.
1974 California Department of Water Resources, Bulletin 160-74, *The California Water Plan*, November 1974, p.89, Table 16. (The figures are "applied" rather than net. The report does not state net figures. Scenarios II for 1990 and III for 2020 are based on DWR statement on p.4.)
1983 California Department of Water Resources, Bulletin 160-83, *The California Water Plan*, December 1983, p. 169-170, Tables 50-53.
1987 California Department of Water Resources, Bulletin 160-87, *California Water: Looking to the Future*, November 1987, p.16.
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1998 California Department of Water Resources, Bulletin 160-98, *The California Water Plan Update*, November, 1998, Vol. 1, p.4-52, Table 4-26.

[45] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994. From DWR's "Applied" water data, "normalized" 1990 year scenario, and other data below from various DWR tables and figures from Bulletin 160-93.

[46] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Vol. 1, p.49.

[47] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Executive Summary, p. 25.

[48] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Executive Summary, p. 25. (using "depletion" figures which appear to match the data in figure 3-1, Vol. 1, p.49).

[49] Total of "other outflow" and "environmental", a category which is not desegregated for 1960. Assumes total water resources of 85 mafy for 2020 consistent with 1960 and 1990 data.

[50] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Vol. 1, p.142, table 6-1, for 1990 and 2020 data. 1960 data from US census (See graph of California population earlier in this chapter).

[51] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Executive Summary, pp. 20-21 for 1990 and 2020 data. 1960 data interpolated from 1957 and 1966 report data..

[52] This graph is based on DWR Bulletin 160-93 rather than Bulletin 160-98 due to changes in methodology made by DWR in the 1998 report which do not allow comparison of data. The basic trends have continued.

[53] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Vol. 1, p.49. 1960 figure estimated from

[54] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Executive Summary, p. 25.

[55] California Department of Water Resources. *California Water Plan Update, Bulletin 160-93*. 1994, Executive Summary, p. 25. (using "depletion" figures which appear to match the data in figure 3-1, Vol. 1, p.49).

[56] Solley, W.R., R. Pierce, and H.A. Perlman. 1998. Estimated Use of Water in the United States in 1995. U.S. Geological Survey Circular 1200. Denver, CO.

[57] California Department of Water Resources, Bulletin 160-87, *California Water: Looking to the Future*,November 1987,, p.23.

[58] Kahrl, William L., et al. *The California Water Atlas*. California Department of Water Resources, 1979. p. 3.

[59] Lloyd Fryer, 2002. Kern County Water Agency, Presentation to DWR Bulletin 160-03 Advisory Committee.

[60] *National Audubon Society v. Superior Court of Alpine County*, 33 Cal. 3d 419, 189 Cal. Rptr. 346 (1983), cert. denied, 464 U.S. 977 (1983).

[61] California Department of Water Resources, 1994, *California Water Plan Update*, Bulletin 160-93, Vol. 1, p.57.

[62] California Department of Water Resources, 1994, *California Water Plan Update*, Bulletin 160-93, Vol. 1, p.57.

[63] California Department of Water Resources, 1994, *California Water Plan Update*, Bulletin 160-93, Vol. 1, p.5.

[64] California Department of Water Resources, 1994, *California Water Plan Update*, Bulletin 160-93, Executive Summary, p.9.

[65] Hartshorn, J.K., Brickson, Betty, *The Layperson's Guide to California Water*, 1995, Water Education Foundation, p.21.

[66] Gerald R. Zimmerman, 2002. Executive Director, Colorado River Board of California, Presentation to DWR Bulletin 160-03 Advisory Committee. http://www.waterplan.water.ca.gov/b160/committee/meetings.html

[67] Hartshorn, J.K., Brickson, Betty, *The Layperson's Guide to California Water*, 1995, Water Education Foundation, p.22-23.

[68] The facility in Santa Barbara, for example, is not being run due to the high operating costs even though it was fully paid for.

[69] "The SWP, managed by the Department of Water Resources, is the largest state-built, multi-purpose water project in the country. Approximately 19 million of California's 32 million residents receive at least part of their water from the SWP. SWP water irrigates approximately 600,000 acres of farmland. The SWP was designed and built to deliver water, control floods, generate power, provide recreational opportunities, and enhance habitats for fish and wildlife." California Department of Water Resources, *Management of the California State Water Project.* Bulletin 132-96. p.xix.

[70] California Department of Water Resources, 1996, *Management of the California State Water Project*. Bulletin 132-96.p.xix.

[71] Three small reservoirs upstream of Lake Oroville — Lake Davis, Frenchman Lake, and Antelope Lake — are also SWP facilities. California Department of Water Resources, 1996, *Management of the California State Water Project.* Bulletin 132-96.

[72] California Department of Water Resources, 1996, *Management of the California State Water Project*. Bulletin 132-96.

[73] The North Bay Aqueduct was completed in 1988. (California Department of Water Resources, 1996, *Management of the California State Water Project*. Bulletin 132-96.)

[74] The South Bay Aqueduct provided initial deliveries for Alameda and Santa Clara counties in 1962 and has been fully operational since 1965. (California Department of Water Resources, 1996, *Management of the California State Water Project.* Bulletin 132-96.)

[75] Carrie Anderson, 1999, "Energy Use in the Supply, Use and Disposal of Water in California", Process Energy Group, Energy Efficiency Division, California Energy Commission, p.1.

[76] Average deliveries for 1980-89 were just under 2.0 mafy, deliveries for 1990-99 were just over 2.0 mafy. There is disagreement regarding the ability of the SWP to deliver the roughly 4.2 mafy that has been contracted for.

[77] The San Luis Reservoir is jointly owned by the Department and the U.S. Bureau of Reclamation, which operates the Central Valley Project.

[78] The SWP's share of gross storage in the reservoir is about 1,062,000 acre-feet.

[79] United States Bureau of Reclamation, 2002. http://www.usbr.gov/main/what/who.html

[80] United States Bureau of Reclamation, 2002. http://www.usbr.gov/main/written/wc.html

[81] California Department of Water Resources, Bulletin 160-98, *The California Water Plan Update*, November, 1998, p.3-25.

[82] According to MWD, "Metropolitan's annual dependable supply from the Colorado River is approximately 656,000 acre-feet -- about 550,000 acre-feet of entitlement and at least 106,000 acre-feet obtained through a conservation program Metropolitan funds in the Imperial Irrigation District in the southeast corner of the state. However, Metropolitan has been allowed to take up to 1.3 million acre-feet of river water a year by diverting either surplus water or the unused portions of other agencies' apportionments." Metropolitan Water District of Southern California, 1999, "Fact Sheet" at: http://www.mwd.dst.ca.us/docs/fctsheet.htm.

[83] Gerald R. Zimmerman, 2002. Executive Director, Colorado River Board of California, Presentation to DWR Bulletin 160-03 Advisory Committee.

[84] Metropolitan Water District of Southern California, 1999, http://www.mwd.dst.ca.us/pr/powres/summ.htm.

[85] The five pumping plants each have nine pumps. The plants are designed for a maximum flow of 225 cubic feet per second (cfs). The CRA is designed to operate at full capacity with eight pumps in operation at each plant (1800 cfs). The ninth pump operates as a spare to facilitating maintenance, emergency operations, and repairs. Metropolitan Water District of Southern California, 1999, Colorado River Aqueduct: http://aqueduct.mwd.dst.ca.us/areas/desert.htm, 08/01/99.

[86] Metropolitan Water District of Southern California, 1996, "Integrated Resource Plan for Metropolitan's Colorado River Aqueduct Power Operations", 1996, p.5.

[87] Metropolitan Water District of Southern California, 1996, "Integrated Resource Plan for Metropolitan's Colorado River Aqueduct Power Operations", 1996, p.5.

[88] Metropolitan Water District of Southern California, 1996, "Integrated Resource Plan for Metropolitan's Colorado River Aqueduct Power Operations", 1996, p.5.

[89] Metropolitan Water District of Southern California, 1999, "Summary of Metropolitan's Power Operation". February, 1999, p.1, http://aqueduct.mwd.dst.ca.us/areas/desert.htm.

[90] Metropolitan Water District of Southern California, 1999, http://www.mwd.dst.ca.us/pr/powres/summ.htm. MWD provides further important system information as follows: Metropolitan owns and operates 305 miles of 230 kV transmission lines from the Mead Substation in southern Nevada. The transmission system is used to deliver power from Hoover and Parker to the CRA pumps. Additionally, Mead is the primary interconnection point for Metropolitan's economy energy purchases. Metropolitan's transmission system is interconnected with several utilities at multiple interconnection points. Metropolitan's CRA lies within Edison's control area. Resources for the load are contractually integrated with Edison's system pursuant to a Service and Interchange Agreement (Agreement), which terminates in 2017. Hoover and Parker resources provide spinning reserves and ramping capability, as well as peaking capacity and energy to Edison, thereby displacing higher cost alternative resources. Edison, in turn, provides Metropolitan with exchange energy, replacement capacity, supplemental power, dynamic control and use of Edison's transmission system.

[91] Gerald R. Zimmerman, 2002. Executive Director, Colorado River Board of California, Presentation to DWR Bulletin 160-03 Advisory Committee. http://www.waterplan.water.ca.gov/b160/committee/meetings.html

[92] The service area's population of nearly 16 million is expected to grow by about 225,000 people a year. By the year 2010, Metropolitan's consumer population is projected to be about 19.1 million and water demands are expected to increase from the present 3.4 million acre-feet per year to about 4.3 million during normal weather conditions. (Metropolitan Water District of Southern California, 1999, "Fact Sheet" at: http://www.mwd.dst.ca.us/docs/fctsheet.htm.)

[93] Metropolitan Water District of Southern California, 1999, "Fact Sheet" at: http://www.mwd.dst.ca.us/docs/fctsheet.htm. Summary of Metropolitan's Power Operation. February, 1999. Metropolitan generates hydroelectric energy within its system. MWD "sells energy from 15 small and conduit hydroelectric units in its Southern California water distribution system. The units have a combined peak capacity of approximately 101 MW, and the energy from the units is sold to DWR, Edison and PG&E under long-term contracts. A total of approximately 330 GWh per year is sold from these power plants. It also owns and operates

five water filtration plants, which currently require approximately 30 GWh of energy annually. This energy is provided by the local serving utility under retail tariffs.

[94] Metropolitan Water District of Southern California, 1999, "Fact Sheet" at: http://www.mwd.dst.ca.us/docs/fctsheet.htm.

[95] Metropolitan Water District of Southern California, 2000. *The Regional Urban Water Management Plan for the Metropolitan Water District of Southern California*, p.A.2-3.

[96] "About 1.36 million acre-feet per year (34 percent) of the region's average supply is developed locally using groundwater basins and surface reservoirs and diversions to capture natural runoff." Metropolitan Water District of Southern California, 1996, "Integrated Resource Plan for Metropolitan's Colorado River Aqueduct Power Operations", 1996, Vol.1, p.1-2.

[97] Wilkinson, Robert C., 2000. *Methodology For Analysis of The Energy Intensity of California's Water Systems, and an Assessment of Multiple Potential Benefits Through Integrated Water-Energy Efficiency Measures*, Exploratory Research Project, Ernest Orlando Lawrence Berkeley Laboratory, California Institute for Energy Efficiency.

[98] See discussion of applicable regulations in the appendix.

[99] Burton, Franklin L., 1996, Water and Wastewater Industries: Characteristics and Energy Management Opportunities. (Burton Engineering) Los Altos, CA, Report CR-106941, Electric Power Research Institute Report, p.ES-4.

[100] Approximately 71 percent of the U.S. population (or 176 million people) is served currently by publicly owned treatment works (POTWs). The municipal wastewater treatment industry is composed of over 15,000 plants that handle a total flow of about 28,000 million gallons per day (mgd), according to the 1988 Needs Assessment Survey conducted by EPA. In the next 20 to 30 years, the U.S. Environmental Protection Agency (EPA) has estimated that nearly 87 percent of the U.S. population, or 247 million people, will be served by POTWs. Burton, Franklin L., 1996, Water and Wastewater Industries: Characteristics and Energy Management Opportunities. (Burton Engineering) Los Altos, CA, Report CR-106941, Electric Power Research Institute Report, p.ES-2.

[101] Wastewater systems generally consist of three principal components: collection system (sewers and pumping stations), treatment facilities (including sludge – now termed "biosolids" – processing), and effluent disposal or reuse. Burton, Franklin L., 1996, Water and Wastewater Industries: Characteristics and Energy Management Opportunities. (Burton Engineering) Los Altos, CA, Report CR-106941, Electric Power Research Institute Report.

[102] "In the last five years, the use of UV light as a means of disinfecting wastewater treatment plant effluent has increased significantly. Its use has increases because of (1) the increased awareness o f the impact of chlorine and chlorinated compounds on the environment, (2) improvements in UV hardware, (3) regulations requiring reductions in chlorine residual in plant effluent, (4) regulations governing the storage and handling of chlorine, especially in its gaseous form, and (5) safety and operating concerns in the use and handling of chlorine and dechlorinating agents." Burton, Franklin L., 1996, *Water and Wastewater Industries: Characteristics and Energy Management Opportunities.* (Burton Engineering) Los Altos, CA, Report CR-106941, Electric Power Research Institute Report, p.2-32.

[103] Burton, Franklin L., 1996, *Water and Wastewater Industries: Characteristics and Energy Management Opportunities.* (Burton Engineering) Los Altos, CA, Report CR-106941, Electric Power Research Institute Report, p.ES-2.

[104] "Most of the pipelines in a collection system handling sanitary wastewater are gravity sewers. At certain locations, typically when the sewers reach depths of 20 to 30 ft below ground, it generally becomes cost-effective to lift (pump) the wastewater to a higher elevation." Burton, Franklin L., 1996, Water and Wastewater Industries: Characteristics and Energy Management Opportunities. (Burton Engineering) Los Altos, CA, Report CR-106941, Electric Power Research Institute Report, p.2-5.

[105] Gleick, Peter H. (Lead Author), 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States, The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change*, U.S. Global Change Research Program, Pacific Institute for Studies in Development, Environment, and Security, p.2, http://www.gcrio.org/NationalAssessment/water/.

[106] Gleick, Peter H. (Lead Author), 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States, The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change*, U.S. Global Change Research Program, Pacific Institute for Studies in Development, Environment, and Security,, pp.4. The water sector report includes extensive discussion on many topics. This synthesis highlights the key issues for California.

[107] The net risks to society from such changes have not been evaluated and specific projections of where such changes will occur are speculative. Models project that the frequency and severity of droughts in some areas could increase as a result of regional decreases in total rainfall, more frequent dry spells, and higher evaporation. Models suggest with equal confidence that the frequency and severity of droughts in some regions would decrease as a result of regional increases in total rainfall and less frequent dry spells.

[108] "Increasing CO_2 concentrations in some circumstances can reduce the rate of transpiration from certain plants. This in turn would tend to increase runoff since less water is returned directly to the atmosphere by such vegetation, allowing a greater share of precipitation to reach streams or aquifers. Rising CO_2 concentrations can also increase plant growth, leading to a larger area of transpiring tissue and a corresponding increase in transpiration." Gleick, Peter H. (Lead Author), 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States, The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change,* U.S. Global Change Research Program, Pacific Institute for Studies in Development, Environment, and Security.

[109] Gleick, Peter H. (Lead Author), 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States, The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change,* U.S. Global Change Research Program, Pacific Institute for Studies in Development, Environment, and Security, p.5.

[110] Gleick, Peter H. (Lead Author), 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States, The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change,* U.S. Global Change Research Program, Pacific Institute for Studies in Development, Environment, and Security, pp.5-6. The water sector report includes extensive discussion on many topics. This synthesis highlights the key issues for California.

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[114] Gleick, Peter H. (Lead Author), 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States, The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change,* U.S. Global Change Research Program, Pacific Institute for Studies in Development, Environment, and Security, p.32, citing: Schneider, S.H., P.H. Gleick, L.O. Mearns. 1990. Prospects for climate change. In P.E. Waggoner (ed.) Climate Change and U.S. Water Resources. J. Wiley and Sons, Inc. New York, pp. 41-73; Intergovernmental Panel on Climate Change (IPCC). 1996. Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York; Intergovernmental Panel on Climate Change (IPCC). 1996. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses: Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, New York.

[115] Gleick, Peter H. (Lead Author), 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States, The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change,* U.S. Global Change Research Program, Pacific Institute for Studies in Development, Environment, and Security, p.32.

[116] Roos, Maurice, 2001. Draft materials prepared for the California Energy Commission for the Public Interest Research Program (PIER) on Climate Change.

[117] Gleick, Peter H. (Lead Author), 2000. *Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States, The Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change,* U.S. Global Change Research Program, Pacific Institute for Studies in Development, Environment, and Security, p.69.

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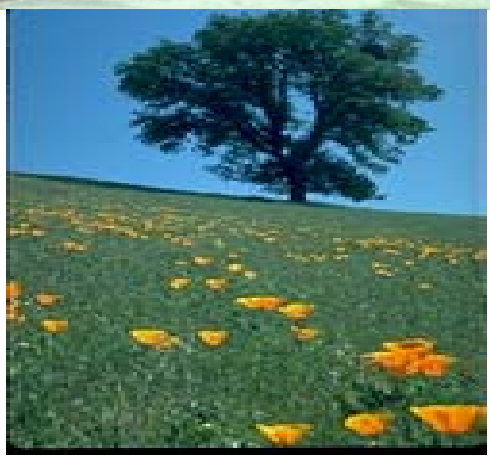
Part 2. Natural Resource Systems, Ecological Systems, and the Potential Impacts of Climate Change and Variability

Introduction

California's ecosystems range from highly productive coastal waters and tidal estuaries to sensitive high alpine meadows, and from expansive deserts to temperate rainforests and fertile valleys. Natural resource systems, often based on the *services* provided by these ecosystems, include rich fisheries, fertile soils for agriculture, and a variety of unique and valuable forest systems. Minerals and petroleum are also a valuable part of California's natural resource endowments.



Some of the potential impacts of climate change and variability on these systems, and on the extraction of services and resources from them, are reviewed in this section. Many interesting and important questions are being raised by stakeholders regarding potential impacts. For example, the incidence of fires ignited by lightning strikes may change in both timing and location with changes in climate. These fires are often difficult to manage due to rough terrain. Coastal mountain regions would be particularly impacted by an increase in weather patterns that produce lightning strikes, especially if it occurs in the fall when the forests and chaparral is dry and fire-prone. Another example of a concern raised by stakeholders is the potential for changes in the fog regimes in California. Valley fog is important to agriculture. Farmers in the San

Joaquin Valley raised the question of whether fog patterns might change as a consequence of climate change. Similar questions have been raised regarding coastal fog patterns.

Potential changes to climate patterns like these could impact natural resource and ecological systems throughout California. Some changes could be beneficial, others could exacerbate existing stresses or create new ones. This section seeks to provide information based on scientific research that has been undertaken on some of these issues. Many important questions remain to be asked, however, let alone answered. In this area it is important to emphasize that potential impacts may not even be recognized at this time. This is in part due to the complex interactions in natural systems. For example, the interactions occurring in predator-prey relations in both natural and managed ecosystems are clearly influenced by climate. Implications for forest and agricultural ecosystems of changes in these relationships may be critical to ecosystem functions. As Field et al. note: "A number of poorly known ecological interactions have the potential to exert strong control over the magnitude and direction of changes in plant communities, as well as other ecosystem responses to climate change."[1] We do know that even a single species of pest or disease can cause widespread and costly damage to both natural and managed ecosystems.

This area of natural resource and ecological systems impacts assessment has benefited in particular from discussions with a wide range of stakeholders. Farmers, foresters, fishers, naturalists, and many others need to continue to be involved in an ongoing dialogue, both to ask important questions regarding these critically important systems, and to provide information that builds our understanding of how they function.

This section looks first at the ecosystems that underpin a number of important natural resource systems in California. It then examines some of the other important natural resource systems that may be impacted by climate change and variability. The following section will discuss potential impacts to human systems such as infrastructure and health.

Ecosystems and Climate

All ecosystems in California, whether natural or managed, will likely be affected by climate change and variability. Temperature changes and shifting precipitation patterns will alter plant and animal communities. Extreme events such as floods, droughts, and wildfires may become more frequent and intense. Plants and animals, already pressured by human encroachment, will be further stressed by climate change and variability. Wildlife will have to adapt to changing habitats; some species will move, others may alter their behavior. Some may not be able to adapt. The number of threatened and endangered species in the state, already the largest in the contiguous 48 states, could rise significantly due these combined stresses.[2] Shaw notes that, "In addition to its critical role in the persistence and distribution of ecosystems and species, climate is also important in determining ecosystem properties and services. Climate is significant in determining soil type and fertility, disturbance regimes (i.e. fire), net primary production, and carbon storage. With changes in climate, these, too, will undoubtedly be affected."[3]

What are Ecosystems?[4]

Ecosystems are communities of plants, animals, microbes, and the physical environment in which they exist. They can be characterized by their biological richness, by the magnitude of flows of energy and materials between their constituent species and their physical environment, and by the interactions among the biological species themselves, that is, by which species are predators and prey, which are competitors, and which are symbiotic.

Several studies have been undertaken to assess the potential ecosystem impacts of climate change on California. In 1991, Daniel Botkin et al. contributed to *Global Climate Change and California: Potential Impacts and Responses*, an analysis of potential impacts of climate change led by Joseph B. Knox.[5] More recently, the Ecological Society of America and the Union of Concerned Scientists published a review of potential impacts of climate change on California's ecosystems by a distinguished team of scientists led by Chris Field of Stanford University.[6] A large number of studies have been done on potential implications of climate change for specific elements of ecosystem functions and processes including marine, terrestrial and aquatic ecosystems, and other elements.[7] This assessment reviews the important questions and key findings from this work.

Field et. al. provide the following description of California's climate as a context for the structure and distribution of California's ecosystems:

Climate Patterns and Ecosystems[8]

California's climate is controlled by broad interactions among the oceans, landforms, and atmosphere. Overall, California's climate shares many features with the climates of the southwest corners of the other major land masses—Europe, Africa, South America, and Australia. All are regions of Mediterranean-type climate, which is characterized by cool, wet winters and hot, dry summers. California receives 80% of its annual precipitation in winter.

In the summer, California's climate is dominated by the Pacific high, a zone of high pressure caused by the descent of dry air lofted high in the atmosphere by intense convection in the northern tropics. The Pacific high pushes the storm track to the north and creates hot, dry summers over most of the state. In the winter, the zone of tropical convection shifts to the southern tropics, and the zone of downwelling dry air and high pressure shifts to the south as well. This southward retreat of the Pacific high allows a parallel shift of the storm track, which opens Northern California to a series of storms arising from low-pressure cells generated over the Aleutian Islands. Usually, the Pacific high offers some protection to Southern California throughout the year, and precipitation totals there are typically lower than along the North coast by a factor of 10.[9] In any given winter, precipitation is very sensitive to the strength and position of the Pacific high.

The climate of coastal California is strongly influenced by the proximity of the Pacific Ocean. Cold, upwelling waters near the coast cool the air masses passing over them, providing a coastal "air conditioner," especially during hot periods when rising inland air masses pull ocean air onshore. This cooled air is usually fog laden, especially in Central and Northern California, where the coastal waters are cold enough to push the air temperature below the dew point. The interaction of topography and coastal fog creates habitats with spectacular local climate contrasts, because low hills can often halt and collect the surface flow carrying the fog.

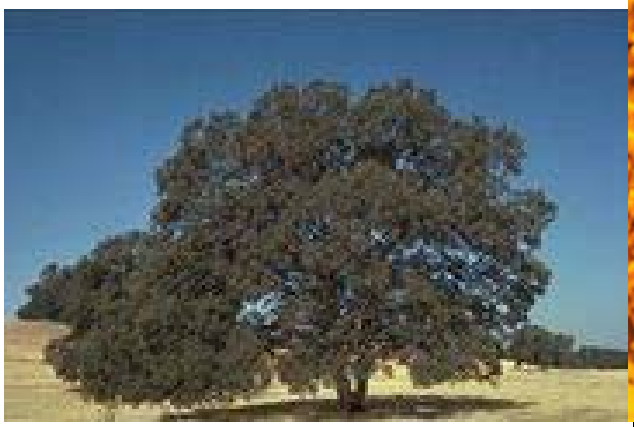
California's topography is another major controller of climate. The coastal mountains and the much higher Sierra Nevada cool the eastward- and southward-moving storms, creating wet western slopes and substantial rain shadows to the east. The coastal ranges are generally too low for profound climate differences between their tops and bottoms, but the Sierras are high enough to create sharp contrasts between the hot desert of Death Valley and alpine tundra on the flanks of peaks that rise higher than 13,000 feet.

Most of the state's ecosystems experience some summer drought. Runoff is also highly seasonal, and the flow of many streams and rivers varies tremendously through the year, with many carrying water for only a few weeks or months. In the larger rivers, flow is now almost exclusively under human control. California has more than 1,200 reservoirs, which regulate most of the state's rivers. Year-to-year variation in climate is important in almost all parts of California. In the past few decades, major droughts and floods, frosts, and hot spells have caused billions of dollars in damages. These weather extremes have also laid the groundwork for follow-on disasters, ranging from devastating fires to biological invasions.

Much of the year-to-year variation in California's climate is connected to the El Niño Southern Oscillation, or ENSO. During the ENSO warm phase (El Niño), the tropical westerlies lose strength, and the warm waters of the western tropical Pacific spread far to the east, bringing much warmer than usual surface waters to the west coasts of North and South America. El Niño effects on California vary across the state but typically include above-normal winter rains and storminess.

Ecosystem Services

A useful approach to understanding the potential implications of climate change and variability is to consider how these changes might impact the *services* being provided by these systems.[10] For example, water storage, timing and quality are provided by watersheds, and flood management is provided by wetlands and riparian systems in flood plains. Pollination and pest control are provided by insects and birds. More obviously, important products from fish to timber are derived from natural systems. Climate change may impact these and many other services. The impacts may be both positive and negative from the perspective of human welfare. To understand the implications of climate change, we need to better understand these services and their value.



Valuing Ecosystem Services[11]

Californians derive many benefits from the state's natural ecosystems. These include the production of a diversity of goods, or extractive benefits, such as seafood, forage, timber, and raw materials for industrial and pharmaceutical products. The harvest and trade of these goods represent an important and familiar part of the economy. Ecosystems also provide us with services—non-extractive benefits—including fundamental life-support processes such as water purification, pollination of crops and wild plants, renewal of soil fertility, and climate regulation. These services are essential not only to the state's agriculture and forestry sectors, but also more broadly to tourism, recreation, human health, and quality of life.

Ecosystem services are generated by a complex of ancient natural cycles that have developed over hundreds of million years. They are absolutely pervasive and yet largely unnoticed by most people. Most of these services that are essential to human existence could not be replaced by technology. Escalating impacts of human activities on natural ecosystems imperil the delivery of these indispensable systems.

Globally, ecosystem services may be worth many trillions of dollars. Yet because they are not traded in economic markets, they carry no price tags that could alert society to changes in their supply or to deterioration of underlying ecosystems and cycles that generate them.

Only by recognizing and fairly valuing the many subsidies and services our society receives from healthy ecosystems will we be able to make wise decisions about resource allocations for the future.

One of the services provided by natural systems for both managed and unmanaged ecosystems is pollination. Field et al. cite several studies indicating that pollination systems may be disrupted by climate change. "If climate change affects the timing of plant or animal life stages—such as when buds burst, when flowers bloom, or when eggs hatch—then vital interactions between species, from pollination to predation, may be disrupted." The team found that:[12]

> There is some evidence that climate change could disrupt plant-pollinator relationships and dispersal of seeds by animals in Mediterranean-climate ecosystems, including California.[13] Pollination by bats, bees, beetles, birds, butterflies, and other animals is required for the successful reproduction of most flowering plants, including both wild and crop species. In California agriculture, pollinators are critical to production of many orchard, field crop, and forage plants, as well as the production of seed for many root or fiber crops. The continued availability of pollinators depends on the existence of a wide variety of habitat types needed for their feeding, successful breeding, and completion of their life cycles.[14]

Summary of Potential Impacts

Field et al. summarize the relationship between existing stresses and the potential impacts of climate change as follows:

> Over the past century, human activities have dramatically altered the natural landscape of California. Our historical legacy includes severe shrinkage and isolation of natural habitats, altered flows in streams and rivers, extensive introductions of non-native plants and animals, and pollution of the air, land, and water. As we enter the 21st century, a powerful new agent—global climate change—will increasingly interact with the human pressures that continue to stress California's ecosystems. In the future, direct impacts generated by the state's rapidly growing human population will be intensified by the impacts of climate change.[15]

Shaw provides further comment on land-use policy and its impact on ecosystems:[16]

> Land use patterns and change are determined by a wide array of governmental, environmental, economic and cultural factors. In the last twenty years in California, land use changes have been driven by a human population that has increased by 44%, a rapidly expanding economy, changes in the tax codes to favor sprawl, and poor land use planning at the local level. After 50 years of dramatic sprawl, California's metropolitan areas and farmlands now cut deeply into once-thriving natural ecosystems. Expanding acreage for agricultural, urban, industrial and transportation systems has caused declines in the spatial extent and connectivity of forests, wetlands, open space and wildlife habitat.

Existing stresses are a key aspect of this assessment. Critical ecosystems, such as wetlands and riparian zones along streams and rivers, have been altered or eliminated. This context, as Field et al. and others point out, is important to bear in mind as climate impacts are considered. The research team provides the following summary of potential impacts for California:

What Might Climate Changes Mean for California Ecosystems?[17]

California's natural ecosystems—communities of plants and animals interacting in a physical environment—span 10 different biological categories, ranging from the cool, wet redwood forests of the North Coast to the hot, dry Mojave and Colorado deserts of the southeast. Many of these natural ecosystems—as well agricultural ones—are highly sensitive to the availability of water. Thus changes in the timing or amount of precipitation over the next century are likely to have a greater impact than changes in temperature. For example,

- Decreased summer stream flows would intensify competing demands for water to meet the needs of agriculture, industry, and urban areas, and to sustain the health of California's aquatic and streamside ecosystems.
- Intensified competition for an already oversubscribed water supply could lower the profitability of water-intensive crops, including alfalfa, cotton, and grapes.

- Reduced summer runoff of fresh water would increase summer salinity in San Francisco Bay, leading to changes in water circulation and quality and complex changes in the food web, including impacts on fish and invertebrates that use the bay as a nursery ground.
- Increases in the amount of winter rains could intensify flooding and landslide hazards.

The highly diverse California landscape includes ecosystem types ranging from desert to temperate rainforest, from largely pristine to intensively managed, and stretching from coastline to mountain ridges. Climate change will inevitably shift the suitable range for each type of ecosystem, as well as the mix of plants and animals and the vital flows of energy and nutrients that occur within them. Some of these changes are already occurring, providing a first glimpse of the kinds of processes and problems that are likely to intensify as climate change continues. For example,

- One species of butterfly, Edith's Checkerspot, is shifting from the southern to the northern limits of its range and from low-elevation to high-elevation sites, a likely consequence of rising temperatures.
- Warming of the California Current in recent decades has been linked to population declines of zooplankton and seabirds known as sooty shearwaters. On the rocky shores of Monterey Bay, southern animal species have increased in the warmer waters while native northern species have declined.
- In kelp forests off the Southern California coast, the proportion of northern, cold-water fish species—e.g., greenspotted rockfish—has dropped by half since the 1970s, and the proportion of southern warm-water fish species—e.g. Garibaldi—has increased nearly 50%.

Other shifts are likely in the future:

- Expanding grasslands will likely encroach on the foothill shrublands of the coastal ranges and the Sierra Nevada.
- At higher elevations, shrubs could proliferate at the expense of forests, and, where the peaks are high enough, forests could expand into the areas now occupied by tundra. In many cases, however, plant and animal species will not be able to shift northward or upslope because the potential habitat has been claimed by development, captured by non-native species, or contains unsuitable soils or other physical limitations.
- In California's agricultural ecosystems, important perennial crops such as fruit, nuts, and grapes will be most vulnerable, because it can take years for farmers to bring more suitable tree and vine cultivars into production to adapt to shifting conditions.

Many California ecosystems are effectively isolated, either as islands surrounded by human development or as remnant ecosystems hemmed in by contrasting soils, geographical features such as mountains, invading non-native species, or other factors. Isolation increases the vulnerability of these communities in the face of even modest climate changes, because it limits the ability of species to persist in place or to migrate in response to shifting conditions. Some of these isolated or "museum" ecosystems are likely to become more biologically impoverished and eventually to disappear if we fail to recognize that persistence in the short term is no guarantee of long-term success. For example,

- Individual redwoods may survive for centuries, even millennia—long past the point where climate changes make growth of new seedlings impossible. The same longevity of individuals that can mask the slow degradation of these landmark California forests can also provide time for restoration efforts.
- Isolated patches of unique grassland, marsh, and aquatic habitats—such as the Serpentine outcrops of Northern California and vernal pools in the Central Valley, which often harbor rare or spectacular species—are so poorly connected with other patches that migrations required by climate change may be difficult or impossible without human intervention.

A large proportion of the effects of climate change on California ecosystems will be indirect; climate change may alter the frequency and/or intensity of extreme weather events such as severe storms, winds, droughts, and frosts in still-uncertain ways. Similarly, the frequency and/or magnitude of some ecologically important processes such as wildfires, flooding, and disease and pest outbreaks is likely to alter as climate changes occur. Altogether, these difficult-to-predict phenomena, driven by shifts in climate patterns, may be more important for the future of California ecosystems than changes in average temperature and precipitation. For example,

- Any increase in Santa Ana wind conditions, combined with warmer, drier summers, could escalate economic and environmental loss to wildfires in California.

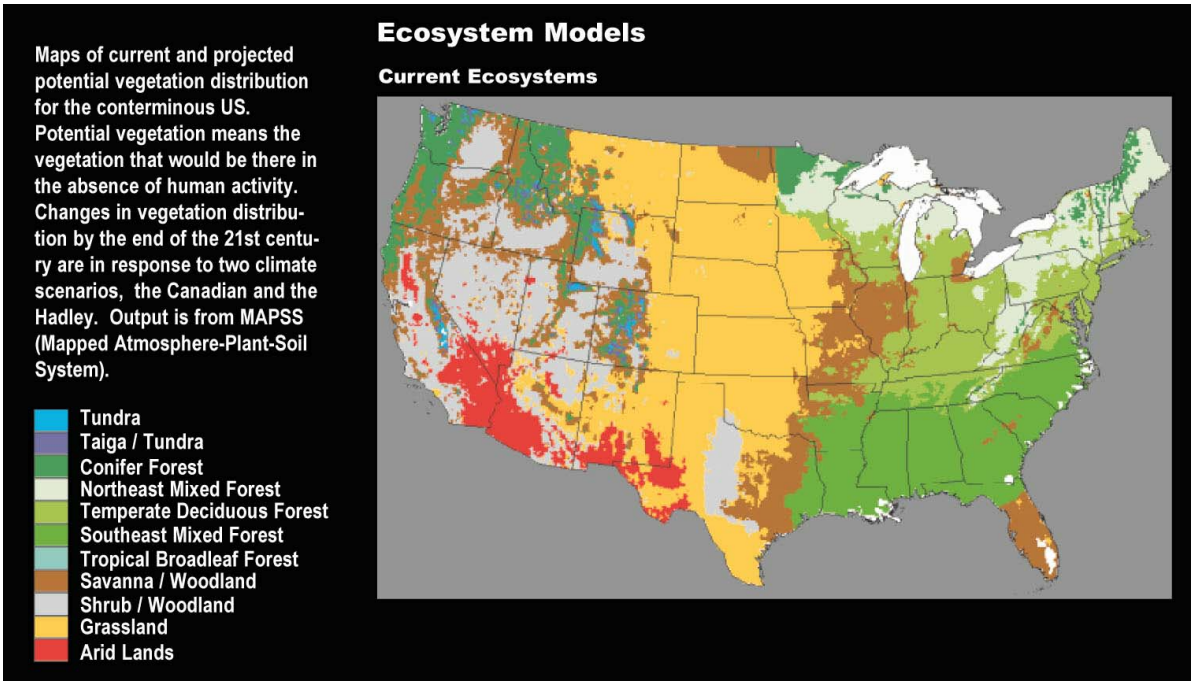
- An increase in the number or intensity of now-infrequent thunderstorms, which form over land and pick up more acids and other pollutants than Pacific frontal storms, may mean more acid rain and increased murkiness (from nutrient enrichment) for Sierra lakes.
- Pests such as pine bark beetles could become more prominent or more destructive if shifts in climate stress trees.
- El Niño warming may encourage toxic algal blooms in bays and estuaries and depress ocean productivity offshore.
- On shore, heavier and/or more frequent El Niño rains could increase the frequency of the rodent population booms that precede hantavirus outbreaks.

Although many California ecosystems are adapted for quick recovery from extreme events, increases in the frequency of such events could push some systems beyond their potential to recover. For example,

- Unlike redwood forests, coastal marine communities such as kelp forests can be destroyed in only a few seasons by disturbances such as severe El Niños. Yet they can also recover much more rapidly than terrestrial forests.
- Chaparral and closed-cone pine forests are adapted to fire and regenerate rapidly from fires that recur at certain intervals; however, fires in these habitats are a major threat to human property and lives in California.

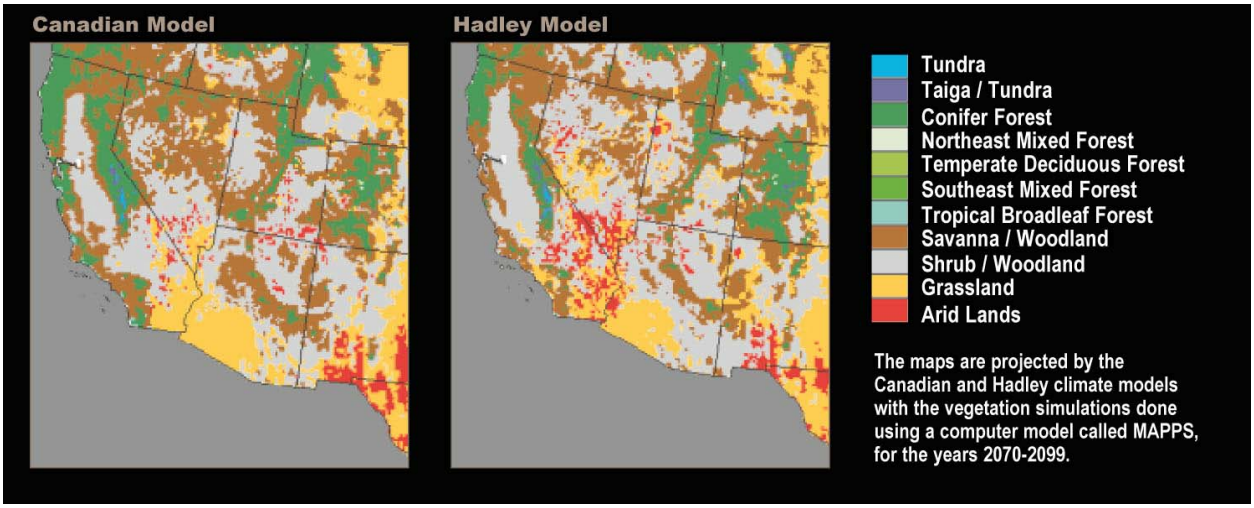
Potential Shifts in Ecosystems Based on Modeling Results

The US national assessment climate modeling indicates important potential changes in ecosystem distribution. Based on the Canadian and Hadley models, the following maps show vegetation change projections based on changes in temperature and precipitation. They are based on "MAPSS – Mapped Atmosphere-Plant-Soil System". The first map shows current conditions across the United States:[18]



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

Changes in the distribution of ecosystem types in the latter part of the 21st century are indicated in the following maps based on the two different global models, again using MAPPS:



Source: National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States.* Report for the United States Global Change Research Program. Cambridge Univ. Press. http://prod.gcrio.org/nationalassessment/

These model runs indicate important changes in distribution. It should be emphasized, however, that these are models using large scales. As models are refined and "downscaled" to finer resolutions, we will gain a better understanding of potential ecosystem changes. Field et. al. make this point as follows:

Downscaled Modeling for California[19]

To get meaningful projections of future rain and snow patterns across California's highly varied landscape, scientists must work at finer scales of resolution than global GCMs provide. Moderate-resolution GCMs, for instance, project average statewide precipitation changes in California of less than 0.02 inches (0.5 mm) a day, year round.[20] Yet studies using models or statistical techniques to achieve higher spatial resolution yield quite a different picture of winter precipitation in a warmer climate. One model reveals a large increase in precipitation over California, but with strong "rain shadows" (dry areas) to the east of the Cascades and the Sierra mountain ranges that are largely invisible to the global models. This regional model projects that winter precipitation over the coast and Sierra will rise by 25% or more.[21] Another high-resolution calculation indicates a similar pattern of striking variations in rainfall across the state.[22] These simulations pinpoint the strongest warming in the Northern Sierra and Central Valley, with drying in the southeastern corner of the state. Such results confirm that climate change is likely to be highly variable across California, and that local impacts may be much greater than statewide averages would indicate.

Distributions of California ecosystems are expected to shift. A number of factors, however, will influence the patterns and outcomes. As Field et al. note:[23]

> As climate conditions change, the map of vegetation types will shift. Tracking where ecosystems will move in a warming climate is not straightforward, because species move individually, and their fate may be altered by changes in the availability of water and nutrients or patterns of fire, drought, or pest attack. Computer models suggest that the arid shrublands on California's foothills may give way to grassy savannas while shrubs replace forests on higher slopes. Trees, in turn, may gain ground upslope. In many parts of California, fragmentation of the landscape by human developments, invasions by non-native species, and air pollution may limit the reestablishment of native ecosystems.

Ecologists caution against the simplistic notion that whole ecosystems will migrate upslope and north as temperatures warm.[24] Shaw notes that:[25]

> Early investigations to determine species and ecosystem distributions under climate change focused on the "climate envelope" approach. Simple models, based on correlations between species distributions and climate, were used to predict how ecosystems might shift with a given step-change in climate. The results suggested ecosystems would migrate to meet their optimal climate without disruption, which is *now considered highly unlikely*.

Noting that "the fossil record supports the idea that plants move as climate changes," scientists point out that *rates of change* are critical to the ability of systems to adapt, and other factors including community structure, soils, barriers are important determinants of whether and how quickly ecosystems and species can adapt.[26] They also note that "analysis of pollen captured in lake sediments shows that even relatively small changes in climate such as the 1º F cooling that occurred during the Little Ice Age in the 17th century are followed by a change in plant species."[27] Field et al. cite four reasons that a smooth migration is unlikely to come about:[28]

1. Species clearly move as individuals and not as complete communities.
2. Increased temperature can lead to changes in the availability of water or nutrients—changes that benefit some species and stress others.
3. Extreme events such as severe droughts are often more limiting to plant survival than average conditions, so average temperature may not be a good predictor of where plants would move.
4. Warming could alter the risk of fire, disease, or pest attacks that affect the fate of species and their ecological communities.

The ability of ecosystems to adapt to change is directly related to the ability of species to survive. Shaw explains that notions of ecosystem shifts have changed:[29]

> The next generation of models—dynamic global and regional ecosystem models involving transient changes in climate—predict that ecosystems will not shift as intact entities. More likely, significant changes in the structure of the ecosystems are likely. Species richness is expected to decline with significant reorganizations of species community assemblages. Species will respond differently due to differences in competitive abilities, migrations and dispersal rates, and recovery rates from disturbance. As a result, new combinations of species are likely to arise.
>
> Reorganization of ecosystem structure in California will be particularly extreme because of the state's topographic complexity that results in steep gradients in temperature and precipitation. As a result, many of California's natural ecosystems will be in early successional states with simpler structure and decreased species diversity.

Biodiversity and Climate Change

California's biodiversity is a unique and valuable asset that may be impacted by climate change. It is already under stress for a variety of reasons. Field et al. review some of what has been lost:[30]

> Since 1850, California has lost 80% of its coastal wetlands, 96% of its interior wetlands, and 99% of its valley grassland,[31] and most of California's remaining grasslands are dominated by grasses introduced from other continents.[32] California's flora also includes the largest number of threatened and endangered native species of any state.[33] Most of the freshwater fish native to Southern California are extinct, rare, or endangered.

California Red-legged Frog (Rana aurora draytonii)

Southern California Steelhead Trout

Threatened and Endangered Species

Evidence of the challenge is provided by the growing list of listed species. California now has the largest number of listed species of any state other than Hawaii.

State and Federally Listed Plants and Animals in California[34]

Plants	
State-listed endangered	131
State-listed threatened	20
State-listed rare	67
State candidate for listing, endangered	2
State candidate for listing, threatened	0
Federally listed endangered	136
Federally listed threatened	48
Federally proposed endangered	2
Federally proposed threatened	0
Both State and Federally listed	120
Animals	
State-listed Endangered	47
State-listed Threatened	30
Federally listed Endangered	77
Federally listed Threatened	40
State candidate (Endangered)	1
State candidate (Threatened)	0
Federally proposed (Endangered)	3
Federally proposed (Threatened)	1
Federally proposed (Delisting)	2
Total number of animals listed (includes subspecies & population segments)	146
Total number of candidate/proposed animals for listing	5
Number of animals State listed only	29
Number of animals Federally listed only	69
Number of animals listed under both State & Federal Acts	8

Sources: Plants: http://www.dfg.ca.gov/whdab/html/plants.html
Animals; http://www.dfg.ca.gov/whdab/html/animals.html (As of January 2002)

Useful Web Sites Regarding Protected Species

Species Lists
Plants: http://www.dfg.ca.gov/whdab/html/plants.html
Animals; http://www.dfg.ca.gov/whdab/html/animals.html

Laws Governing Protected Species
http://www.dfg.ca.gov/hcpb/species/t_e_spp/tespp.shtml
California ESA http://www.dfg.ca.gov/hcpb/ceqacesa/cesa/incidental/cesa_policy_law.shtml
Federal ESA http://endangered.fws.gov/esa.html

Habitat Loss

The number of species facing extinction is directly related to habitat, as Field et al. observe:[35]

> Predicting the impacts of future climate change on biodiversity is a major challenge, but one guided by key principles. Perhaps the most important of these principles is known as the species-area relationship. This is the trend for the number of species to decline as the size of available habitat decreases or its isolation increases.[36] The large, slow-growing organisms that dominate many ecosystems may persist as non-reproducing adults for extended periods, but they will, at least in theory, be the species most likely to disappear over time as patches of available habitat shrink.[37]

Habitat area, and connections between key elements of habitats such as riparian corridors connecting mountains to the sea, are critical to biodiversity. Field et al. note that "many of California's rare and endangered organisms occur only in remnant or isolated habitats." They note further that:[38]

> When suitable habitat disappears, species disappear. One study reports that 5% to 10% of California's native plants would no longer find suitable habitat within the state if temperatures warmed 5º F.[39] At least one California species, Edith's Checkerspot butterfly, is already shifting to the coolest parts of its range, most likely because of warming.[40] Changes in the abundance of particularly desirable or noxious species are difficult to predict, yet these may be responsible for some of the largest ecological impacts of climate change. California's current system of protected areas is not representative of the state's environments or its biological diversity, and many reserves are very small. Even an expanded and more representative system of reserves will not necessarily protect the state's rare and endangered plants and animals against climate change unless a concerted effort is made to link isolated reserves and to keep suitable migration corridors open. Finally, climate change may create indirect threats to biodiversity by disrupting vital interactions between species, from predation to pollination.

Invasive Species

Invasive species have become an important issue in California. From star thistle in rangeland areas throughout the west to aquatic invaders riding in the ballast water of ships, introduced species are competing with natives for habitat. As Field et al. observe, habitat loss and invasive species are linked:[41]

> The state's lakes, rivers, and streams are often dominated by introduced fish. Indeed, 37% of the fish species in the state are introduced. About 8% of the mammal species and 2% of the birds are also introduced.[42] The difficulties of migrating from isolated reserves to suitable new habitats could be further aggravated by an abundance of alien invading species, most of which are successful invaders *precisely because they are excellent colonists*. Increasingly, rare and endangered species are held almost as prisoners by alien invaders in limited and sometimes deteriorating habitats. Star thistle, which already infests 22 million acres of California, can render annual grassland useless for grazing and miserable for recreation.[43]

Shaw explains that: "non–native species threaten native species by competing with them for critical resources, preying on them, hybridizing with them, or changing the character of the environment. Where climate changes more rapidly than species can migrate or barriers to dispersal exist, native species may be less well adapted to establishing themselves in new climate regimes than the non-native invaders. Thus, climate change could further facilitate biological invasions and decrease the biodiversity in a state where 359 species are already federally listed as endangered."[44]

Climate Change, Natural Systems, and Fire

Fire regimes in California are both a necessary and beneficial element of natural systems and a fearsome threat. In the arid west, fire regimes are sensitive to climate conditions. Risk of damage from fire has been increased by human activities, including forestry practices and suppression of fires for decades. Increasing development in fire-prone areas has increased the risk and made controlled burns more difficult and risky.

Climate change and variability may influence fire systems in several ways: First, an oscillation between periods of increased precipitation and periods of drought, as projected in some scenarios, will increase fuel loads and then expose them to extreme fire conditions. Field et al. note that "In the Santa Barbara region over the past 500 years, unusually wet decades have been followed a few years later by an increase in large chaparral fires."[45]

Second, warmer temperatures and consequent low moisture content in soils and fuel create increased fire risk. Heat waves and high winds would exacerbate this condition. Studies cited in Field et al. found that:[46]

> Fire behavior models predict a sharp increase in both ignition and fire spread under warmer temperatures combined with lower humidities and drier fuels.[47] One study, for example, combined a forest dynamics model and a fire model to look at Sierra wildfires under several different climate scenarios.[48] The results showed that the severest effects on fires would be provoked by an expansion of the fire-prone mixed conifer forest and a corresponding reduction in the red fir forest that occupies the next higher elevation zone. This change in forest composition was accompanied by substantial increases in both fire frequency and area burned.

The Southwest assessment also found that: "Fire occurrence patterns have been linked with drought indices, El Niño Southern Oscillation conditions, and synoptic-scale climate processes."[49]

Finally, increases in the incidence of lightening strikes may result from changing climate conditions. (A study on lightning is included in this section.)

Fire is already a serious concern in California. At the urban-wildland interface there is particular danger of to property and life. Yet fire is a positive and necessary process in California's ecosystems. Many plants actually depend on periodic fire cycles to maintain health and even for some seeds to germinate. As Field et. al. note: [50]

> Wildfires are a fundamental regenerative force, vital for the long-term health of many classically "Californian" ecosystems. Chaparral shrub communities and closed-cone pine forests both evolved in the presence of fire and have developed adaptations that allow them either to survive fires and resprout from the ashes or to reestablish from seed after a fire. Chaparral communities, for instance, harbor species of annual plants whose seeds germinate after a fire[51] and grow actively for only a year or two until they are shaded out by recovering shrubs. The seeds of these annuals then persist in the soil until the next fire. In many of California's forests, fire was historically common in the understory, where it consumed litter and controlled the hazard of giant, catastrophic fires. Even in moist coastal redwood forests, fires burned on average every six to eight years over the last 270 years.[52] Because of human developments in these fire-prone settings, wildfire has also become a destructive force in California. Since 1923, the 20 largest fires in California have destroyed more than 8,000 structures and taken 42 lives.[53]

> Fire has been a key ecological and evolutionary force in California's forest, shrub, and range systems for thousands of years. In the prehistoric Sierra Nevada, for example, ground fires recurred every 5 to 10 years in woodlands and grasslands, every 4 to 20 years in pine and mixed conifer forests, and every 15 to 40 years in higher elevation red fir forests.[54]

Improved scientific understanding of fire dynamics and the application of management tools such as GIS mapping and modeling has improved fire management. A particularly interesting finding of the Southwest assessment is the relationship of climate to fire cycles evident in the tree-ring record.[55]

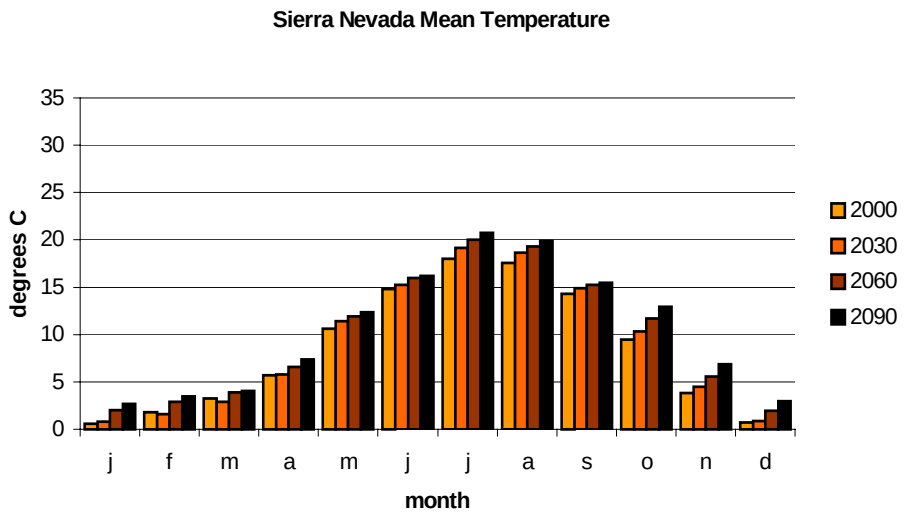
> Reconstruction from tree-ring data of wildfire occurrence in the Southwest reveals that simultaneous changes occurring after 1700 reflect climate forcing of wildfire regimes over interannual to centennial time scales.[56] Research by Swetnam et al.[57] highlights the importance of understanding how lag times between climatic events and vegetation response influence subsequent fire pat-terns. These lag times have important implications for long-range fire hazard forecasting and ecosystem management. For example, based on a 300-year record of climate and fire derived from tree-ring analysis, a pattern of one or more wetter-than-normal El Niño winters in the Southwest, followed by a drier-than normal La Niña winter, establishes preconditions for unusually large and intense wildfires.[58] Further, certain kinds of episodic ecological disturbances, such as insect outbreaks, may be traceable to patterns in climatic variability.[59]

Anthony L. Westerling et al. at Scripps have modeled fire response to climate change in the Sierra Nevada.

Modeling Sierra Nevada Wildfire Season Severity and Suppression Costs under a Climate Change Scenario.

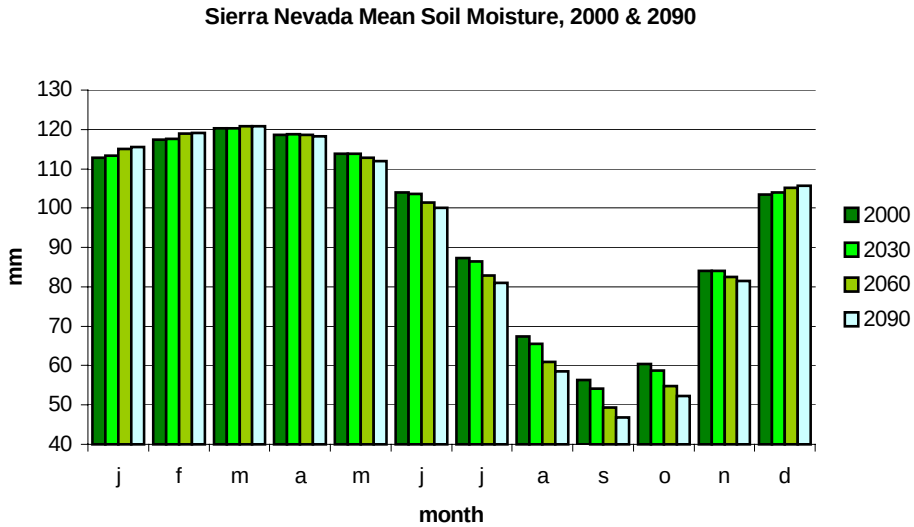
A. Westerling, N. Knowles, D. Cayan
Scripps

Statistical forecast models for fire season severity and fire suppression costs were developed for the Sierra Nevada and used to analyze the change in mean severity and suppression cost from present day conditions to climate change scenarios for 2030, 2060 and 2090. Statistical models estimate normalized area burned and fire suppression costs in constant 2000 dollars based on relationships between fire season severity, represented in a fire history for the Sierra Nevada, and soil moisture and maximum temperature indices.



Daily max temperatures increase during the summer months in this scenario, indicating greater potential for fire ignition, and leading to reduced soil moistures.

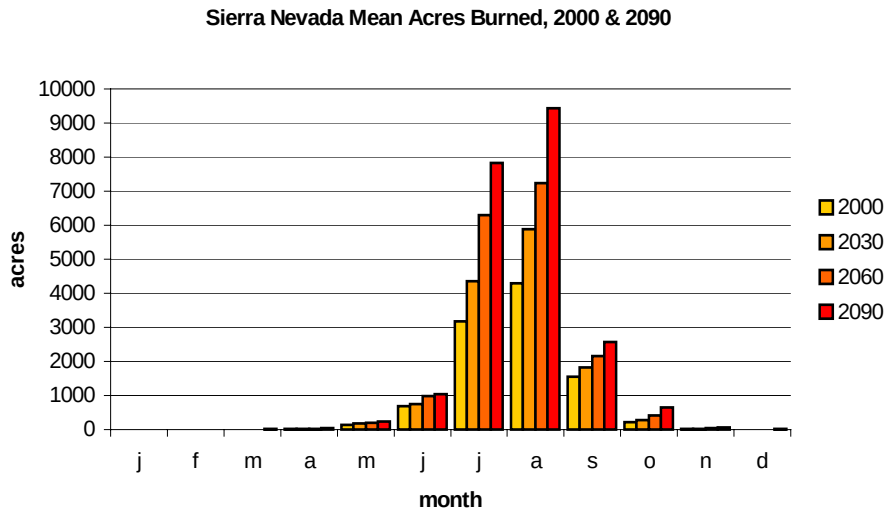
The Sierran fire history, including area burned and suppression costs, is reconstructed from 30 years of U.S. Forest Service fire reports. Daily soil moisture for the Sierra Nevada is generated at a 4 km resolution using the Bay-Delta Watershed Model (BDWM), a physically based, soil-moisture accounting model. Statistical models of fire season severity and fire suppression costs estimated for thirty years of moisture indices generated by the BDWM for current conditions are applied to BDWM moisture indices produced for global change scenarios under the Parallel Climate Model (PCM). The PCM is a modern, high fidelity representation of the global climate system, which has been shown to produce realistic simulations of historical ocean and atmosphere responses to increasing greenhouse gas concentrations.



Soil moistures show the largest relative declines in mid to late summer, indicating drier, more flammable fuels

The results for this climate change scenario illustrate *relative* shifts in mean for fire season severity, comparing

modeled contemporary fire season severity to modeled future scenarios. Modeled fire season distributions are not directly comparable to contemporary observed levels of area burned or dollars spent on suppression costs. All of these changes are driven by shifts in temperature—variables like wind, precipitation, and fuel type are held constant from the historical era.



Modeled mean monthly acres burned show large percentage increases, with July and August mean area burned more than double by 2090. Note that these months show an increase of about one third per scenario (2030, 2060, 2090).

Margaret Torn et al. at the Lawrence Berkeley Laboratory analyzed the potential implications of climate change on fire regimes for California in an interesting paper available on the web at: http://eande.lbl.gov/CBS/pubs/wild.html.[60] They found significant increase in fire risk under future climate conditions.

An important question requiring further research is the potential implications of changes in lightning-induced fires. Lightning tends to strike in places that are difficult for firefighters to reach. For this reason, it is more difficult to react quickly and get a jump on fires resulting from lightening strikes. Once fires get out of control, they can spread rapidly and cause major damage.

Warm, moist air rising to form thunderheads is one source of lightening. This is common in Northern Mexico and into the Southwest with the "monsoons" of summer. Lightening-induced fire are a regular feature in the mountains of this region.[61] This weather pattern has generally not been a feature of California's coastal range, although lightning does strike regularly in the Sierra Nevada during summer thunderstorms, and fires result.

Lightening may be an important concern in the context of climate change in California. The Southwest Regional Assessment also identified lightning-caused fires as a concern.[62] Dettinger et al. have taken an initial look at lightning patterns in the context of climate change.[63] Further research on the subject would be potentially important for fire preparedness.

Useful Web Sites for Fire-Related Issues

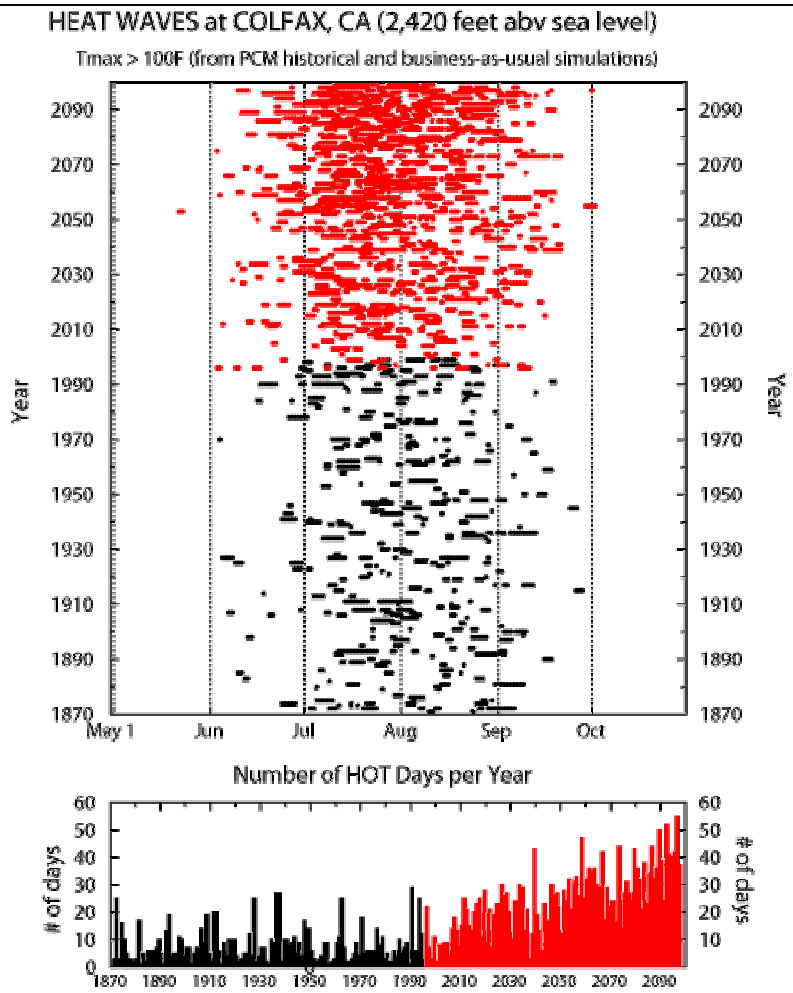
http://www.dri.edu/Programs/CEFA/
http://www.fs.fed.us/r3/fire
http://meteora.ucsd.edu/cap/summer_lightning.html
http://www.fire.ca.gov/20largefires_structures.html

Potential Impacts of Extreme Temperature Excursions

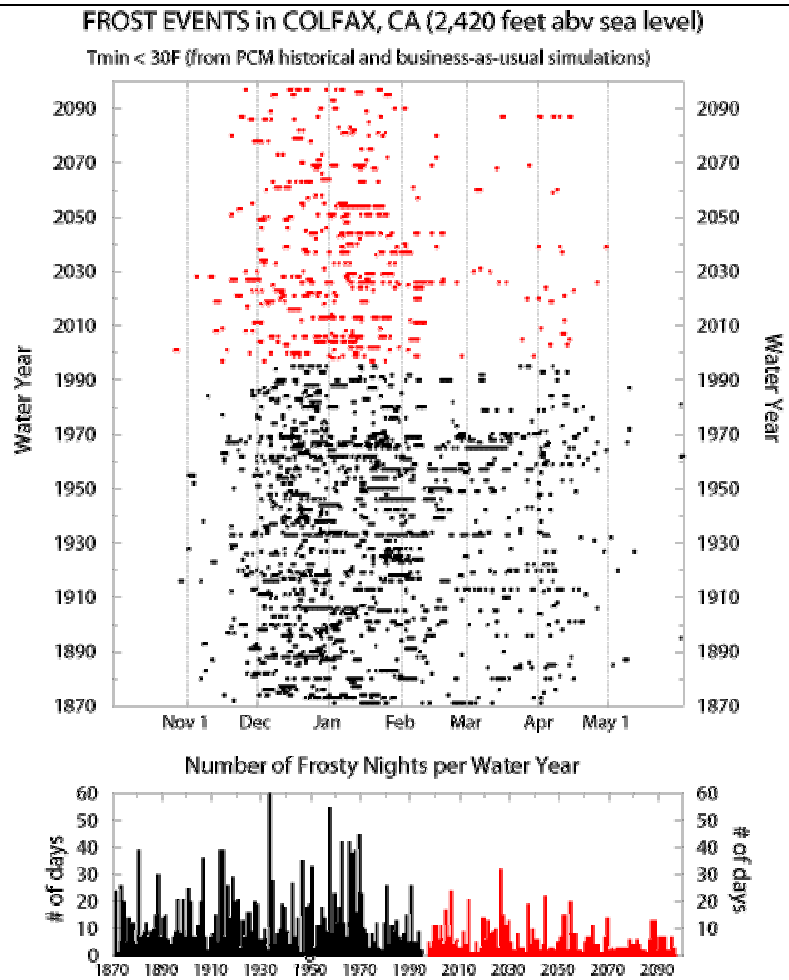
Mike Dettinger, Dan Cayan, Scripps/USGS

Changes in the most extreme temperature excursions may be more pronounced and more important than the projected changes in mean temperatures. The Parallel Climate Model at the National Center for Atmospheric Research projects a 3°C warming over California by the end of the 21st Century, a projection near the cool end of the spectrum of futures that come from modern climate models.[64] Three degrees doesn't seem like much, but consider what happens to the occurrence of really cold days and really warm days under such a scenario.

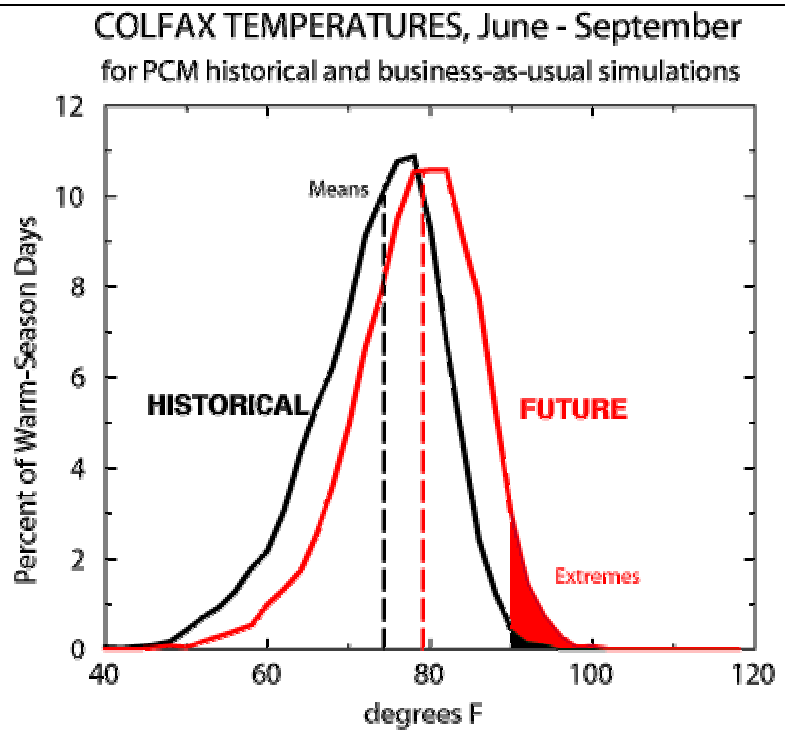
The figure below shows the distribution of days on which simulated temperatures (statistically interpolated by Michael Dettinger, USGS to the long-term weather station at the town of Colfax in the foothills of the Sierra Nevada above Sacramento) exceed 100°F in a historical simulation and in its continuation through the 21st Century. Most such days occur between about the middle of June and the middle of September. As time progresses (upward in the top panel), such days--which are indicated by dots in this plot-- become more and more common, under the greenhouse-warming scenario. The bottom panel counts the number of such days each year, and illustrates a quadrupling of the number of really hot days at this locale by the end of the 21st Century.



At the other end of the thermometer, the figure below shows (in the same format) the distribution of "frost days" (days in which the minimum temperatures dip below 30F) in the same simulations. Historically, frost days occurred mostly from December through February, with relatively frequent occurrences also in April and May. In the 21st century, the numbers of frost days decline markedly (bottom panel) and the frosts are rapidly restricted to only the December-January period.



Why are the projected changes at the extremes so severe, if the changes in the average temperatures are relatively modest? Consider the figure below, which compares the statistical distributions of warm-season, daily-mean temperatures in the course of the historical simulation and in the course of the future simulation. The full range of simulated temperatures is indicated along the horizontal axis and the frequency at which each temperature occurs is indicated along the vertical axis. There is about a 5°F warming between the historical and future simulations, averaged over the 1900-1995 and 1996-2095 periods, respectively). This warming moves the peak of the temperature distribution to the right about 5°F; likewise--in this simulation--it moves the distribution at the extremes to the right by about the same amount. The change in the number of days with temperature around 80°F is not all that dramatic; e.g., historically, about 9% of days are 80F, whereas about 10% are projected in the 21st Century. However, at the warmest temperatures, the change is more pronounced. The black wedge represents the 0.75% of days that are warmer than 90°F in the historical simulation; the red wedge represents the5.5% of days that are similarly warm in the future simulation.



This is seven times more such very warm days! Thus, near the extremes of a typical probability distribution, a small shift will mean a large change in the frequencies of occurrence. This is actually a rule of thumb that appears to apply to the responses many systems to climate change (e.g., both flood frequencies and low-low soil-moisture conditions change more than do the mean flows and moisture conditions) and even applies in responses to short-term events like El Niños.[65]

Water and Ecosystems

Ecosystems are particularly vulnerable to changes in precipitation and runoff patterns as well as soil moisture, water temperature, quality, and timing. This assessment has focused particular attention on the potential implications of climate change and variability on water systems in California. In addition to the information provided elsewhere, a brief discussion of potential ecosystem impacts is presented here.

Ecologists refer to “limiting factors” in ecosystems as the ones that allow for survival and limit population size and composition. Field et al. note that in California:[66]

> Water—its timing and abundance or lack of it—is the limiting factor in many ecosystems. The effects of climate change will therefore be most profound on freshwater systems, but coastal ecosystems will also be affected. The cumulative effects of glacial melting and thermal expansion of the oceans could cause the global average sea level to rise as much as three feet. This would inundate hundreds of square miles of low-lying land,[67] with consequent implications for coastal erosion, inundation of wetlands, salt water intrusion of coastal and delta aquifers, and impacts on developed areas could be devastating to some ecosystems.

Field et al. note further that: [68]

> The CGMs generally indicate a more "vigorous" hydrologic cycle,[69] resulting in increased precipitation and evaporation. Ironically, drought may also increase in some areas. While the total rainfall may rise 20 to 100 percent overall, it may not be distributed evenly.[70] It is possible that some regions will receive below-normal levels. The northern portions of the state are currently much wetter than the southern and inland regions. Climate change may intensify these conditions. The stress on cultivated and natural vegetation could be enormous.
>
> The overall change in soil moisture will depend on whether the increase in winter precipitation is greater than the increase in evaporation. We speculate that, for most of California outside the deserts, the increase in water lost to evaporation may dominate, leading to drier soils in summer.
>
> Water quality may also suffer from climate warming if stronger pollution control measures are not undertaken. Pollutants concentrate when stream flows drop in summer. Saltwater creeps farther and farther upstream in estuaries, and can intrude into coastal aquifers. Algae blooms prodigiously in warm, stagnant waters, depleting oxygen levels, sometimes resulting in large die-offs.

Freshwater Ecosystems

A number of studies indicate that spring runoff flows (April-July) in California rivers are declining.[71] Subsequent low flows in the summer and fall (due to reduced snowpack) will likely affect salinity levels and ecosystems in the Central Valley.[72] Field et al. note that this will have impacts on the Bay-Delta ecosystem as well:[73]

> Higher salinity in the bay can alter circulation within it and affect all levels of the food web, from phytoplankton (algae) to predators, including fish, in complex ways.[74] That is because much of the spatial distribution of organisms is determined by the salinity gradient across the estuary, and the amount and timing of freshwater input has a major influence on the salinity gradient.

> Reductions in runoff could greatly degrade the wetlands that remain in the Central Valley. They now receive considerable runoff from agricultural fields, which contains numerous pollutants, often concentrated by evaporation.[75]

Boesch et al. concur, noting that runoff affects various aspects of coastal marine systems:[76]

> Freshwater runoff affects coastal ecosystems and communities in many ways. The delivery of sediment, nutrients and contaminants is closely linked to both the strength and timing of freshwater runoff. Salinity gradients are driven by freshwater inputs into estuaries and coastal systems, and have strong effects on biotic distributions, life histories and geochemistry. Coastal runoff also affects circulation in estuaries and continental shelf areas; and increases in runoff have the potential to increase the vertical stratification and decrease the rate of thermohaline circulation by adding more fresh water to the system.
>
> Increased runoff would likely deliver increased amounts of nutrients such as nitrogen and phosphorous to estuaries while simultaneously increasing the stratification between warmer fresher and colder saltier water. This would increase the potential for algal blooms that deplete the water of oxygen and increase stresses on sea grasses, fish, shellfish, and benthic communities. Decreased runoff could diminish flushing, decrease the size of estuarine nursery zones, and allow predators and pathogens of shellfish to penetrate the estuary more deeply.

Further up the watersheds and in the higher elevations, lake ecosystems may be impacted by climate changes in several ways. Boesch et al. note that "the response of upland ecosystems to climate change affects the timing and delivery of water and sediment to the coastal zone via interactions among precipitation, storms, landcover, and land use." Field et al. note:

> In mountain lakes, there are a number of potential consequences from changes in the proportion of snow to rain and the volume and timing of runoff from snowmelt. These include alterations in flushing rates (the time required to exchange all the water), length of time of ice cover, amount of mixing, and the inflow of nutrients and other chemicals, including ones that cause acidification.[77]

Boesch et al. concur, noting in the US Assessment that:[78]

> Dams, irrigation projects and other water control efforts have further impacted coastal ecosystems and shorelines by diverting or otherwise altering the flow of water, sediments and nutrients.

Fisheries

As noted above, fisheries will be impacted by changes in flow, temperature, and quality of water. Field et al. note:

> Warmer waters will alter the distribution of coastal fishes, requiring commercial fishing to travel farther or change to different fisheries. Rapid changes to coastal wetlands, including fluctuations in salinity levels, could threaten critical life stages for many marine species, further altering current species distribution. Inland fisheries might also decline as cold-water species do not adapt to warmer waters. California supports the southern-most populations of some salmon and steelhead species that require cold water. As waters warm and stream flows fluctuate, these species could decline drastically or become extinct.[79] Rivers and lakes are likely to have lower levels of dissolved oxygen as waters warm, stressing ecosystems and fish. Freshwater pollution, which could increase as streamflows decrease, will further endanger fish.

Marine and Related Coastal Ecosystems

Marine ecosystems, estuaries, and coastal wetlands are valuable elements of California's ecosystems. Kelp forests, for example, are "among the most productive and diverse communities in the world, comparable to tropical rainforests on land."[80] Boesch et al. note that they are also subject to stresses:[81]

> The role of wetlands in absorbing nutrients and reducing loading to the coastal ocean is widely recognized, as is their value for protecting local communities from flooding; either by damping storm surges from the ocean or by providing storage for riverine floodwaters. Thus, coastal wetlands are undoubtedly some of the most valuable ecosystems in the nation and also some of the most threatened.
>
> Estuaries are extremely productive ecosystems that are affected in numerous ways by climate. Climate change may result in a narrowing of the annual water temperature range of temperate zone estuaries, as winter temperatures increase while summer temperatures increase less because they are moderated by evaporative cooling. This could allow for species range shifts and increase the vulnerability of some estuaries to invasive species.
>
> Climate change and variability compound existing stresses from human activities such as dredging and filling for development; navigation or mineral extraction; altered salinity and water quality resulting from activities in the watershed; and the direct pressures of increasing numbers of people living and recreating in the coastal zone.

A committee established by the National Research Council identified key threats to the integrity of coastal ecosystems. Boesch et al. note that they include "eutrophication, habitat modification, hydrologic and hydrodynamic disruption, exploitation of resources, toxic effects, introduction of non-indigenous species, global climate change and variability, shoreline erosion and hazardous storms, and pathogens and toxins affecting human health."[82]

Changes in Coastal Ecosystems[83]

Researchers revisited sites on Monterey Bay that had been mapped and studied in 1931–1933 and found that southern animal species are increasing as native northern species decline.[84] During the 60 years since the first survey, the annual mean ocean temperature along the shoreline has increased by 1º F, and mean summer maximum temperatures are higher by 4º F. Comparable shifts to dominance by southern species have been noted in kelp forest fish from two sites in Southern California.[85] Since the early 1970s, the proportion of species in fish assemblages that are cold-water, northern species has dropped by about half, whereas the proportion of southern, warm-water species has increased nearly 50%. Similarly, data from California Cooperative Oceanic Fisheries Investigations (CalCOFI) document population increases and northward range expansion of sardine populations over the last 25 years.[86] Collectively, these patterns suggest an ongoing redistribution of marine species along the coast of California that is consistent with predictions for northward shifts in species' ranges in response to ocean warming.

Marine Ecosystem Benefits

Marine and related ecosystems provide a number of valuable benefits which are subject to climate impacts.[87] George Boehlert, Director, Pacific Fisheries Environmental Laboratory, National Marine Fisheries Service, noted in the California workshop[88] that Peterson and Lubchenko[89] review five marine ecosystem services, exclusive of marine fisheries, including:

1. global materials cycling
2. transformation, detoxification, and sequestration of pollutants and societal wastes
3. support of coastal ocean-based recreation, tourism and retirement industries
4. coastal land development and valuation
5. provision of cultural and future scientific values

A specific ecosystem benefit is the moderation of coastal community average temperatures.

Marine fisheries provide a number of services:

1. a source of healthy, high-quality protein for direct consumption
2. employment and multiplier effects from commercial fishing activities
3. recreational (sport-) fishing, estimated at over $5 billion in direct and indirect contributions to the California economy
4. recent forest studies suggest that salmonids contribute significant nitrogen and phosphorus to forest ecosystems as their carcasses decay instream or are carried into the forest by various birds and mammals.
5. support for seabird and marine mammal populations, generating another multi-million dollar "watching" industry.

Kaufman and Dayton[90] note that "The sea provides three kinds of goods."

1. bulk raw materials that have low unit value, such as seaweed and cluepid fishes
2. high-value species like shellfish and top carnivores (billfish, tuna, sharks)
3. materials and live organisms with very high nonfood value, taken in small quantities

Environmental changes in the ocean are already upon us. Retrospective analysis of decadal-scale changes in the North Pacific are a current area of active research, and some evidence exists for increasing incidence of El Niño events over the last decade. Biological changes are evident, such as dramatically reduced zooplankton biomass and seabird populations in waters off the Southern California Bight and distributional changes in many fish populations.

Research on the biological phenomena associated with these changes can be beneficially applied as proxies of anticipated changes that may occur under conditions of climate change. That major changes is already here was pointed out by current paleo-geological research at UCSB. Oxygen isotope analysis of the past 100 years from cores shows that the conditions of warming, and likely increasing mixed layer depth, have occurred since 1916 and accelerated since 1960. A further assessment of the past 11,000 years suggests that conditions since 1960 are unprecedented. The data imply that there has been a significant relaxation of the California Current and a likely strengthening of the countercurrent, leading to lower nutrient levels and lower biological productivity in the region. These plus other results suggests that the California marine region is highly sensitive to climate change, making it an optimal location for research on climate change impacts on marine systems.

Current stresses affecting the region, its natural resources, and economic sectors.

Overfishing; Many stocks of marine fishes off California are overfished or impacted in other ways, such as reductions or impacts to essential habitat. Overfishing has affected the natural state of these populations and can be observed not only in changes in standing stocks but also in truncated age distributions, reduced genetic diversity, and altered predator-prey relationships. Time series of biological information, such as fisheries catch data, are relatively short (typically 30 years or less in duration) and thus our ability to assess the baseline, or natural condition, is limited. This leads to "creeping baseline syndrome", wherein science's view of the natural, or desirable system differs from that free from human impacts. With declining fish stocks, pressure will increase for coastal fish farming ventures, resulting in a new set of stresses, including waste production and coastal space requirements.

Excess harvesting capacity: California's fishing fleets have the ability to harvest more fish than the system can sustain. This represents an ecological problem in that it exacerbates overfishing, and also an economic problem associated with displacements as fish stocks decline. Fishing fleets are highly mobile and are typically able to move from one resource to another; thus the fishing industry is often able to stay ahead of management, creating new problems. A specific problem discussed was the live fish fishery off California, which is poorly managed and is taking far more fish than can be sustained, including fish smaller than the age at first reproduction. In a general sense, fisheries management is conducted on a single species basis and is not able to respond as rapidly as is needed to changing biological and economic conditions.

Ocean as a repository: California's coastal ocean is used as a repository for a variety of wastes, including thermal (from power plants), excess salts from desalination plants, and treated sewage. Nutrient loading, runoff from rains and sewage treatment plants cause changes in the coastal ocean that have been implicated in toxic algal blooms.

Coastal development impacting estuarine/marsh areas: Coastal development has drastically impacted wetlands and salt marshes in California as well as estuaries farther north. This has far-reaching effects on biological populations as well as the interface between freshwater and marine ecosystems.

Changed freshwater inflow to the coastal ocean: Increasing human population leads to increasing water use. The patterns of natural freshwater flow to the coastal ocean is generally reduced, both in total amount and in the seasonal pattern of release. The effects of reduced freshwater flow on the coastal ocean are largely unknown.

Protected species issues: Marine mammals and other protected species such as sea otters in the coastal ocean have captured the interest of the public. While some populations remain at low levels, others have expanded rapidly, leading to conflicts over space and resource use.

Pollution and oil spills: Non-point source pollution from urban and agricultural runoff may interact with other stresses to magnify changes possible due to regional climate change or increased variability. Offshore point sources such as oil and gas platforms may add to this burden due to the at-sea discharge of drilling muds, cuttings, and/or produced waters in federal leases.

How climate variability/change might amplify or dampen stresses or create surprises.

Fisheries are subject to environmental variability in several ways, and extant fisheries management regimes are not particularly skilled at taking environmental variability into account. Biological effects can be dramatic. Fish distributions can change. As shown during El Niño events, northward extensions of pelagic populations occur rapidly and may result in positive stimulus to some fisheries, such as those for tuna or billfishes. Others, such as squid fisheries, may suffer because of lack of availability of the resource to the gear types used. Demersal resources, such as benthic rockfish or most invertebrates (e.g., abalone) respond more slowly to thermal changes, often by a gradual northward extension of the range (if appropriate habitat exists) and a loss of the southern parts of the population. Effects may not be seen for long periods, as much as decades in the case of long-lived fishes which may not even mature or enter the fishery until over age 10. If the total system productivity continues to decline as noted above, higher trophic levels will decline apace. A potential problem here is that with warming and a deepening thermocline, it is possible that upwelling may continue or even increase but will be biologically ineffective because it will no longer bring nutrient-rich water to the surface.

Overfished populations are particularly vulnerable to environmental change and may be at greater risk. As an example, higher storm frequency or longer intervals of elevated thermal conditions may result in poor reproduction for periods sufficiently long to endanger the continued existence of the stock or species. A good example is provided by salmon, where a continued run of consecutive extreme years could cause a local population to go extinct. Overfished populations, which often have truncated age distributions and reduced genetic diversity, may be less able to respond to environmental changes. Economic aspects of fisheries may also be impacted. It is uncertain that the influx of southern species could replace reduced production of traditional coastal fisheries, despite mobility of the fleets. Additionally, mobile fleets from other impacted areas could exert additional local fishing pressure.

Extreme weather events and rising sea level could also have major effects on coastal development with impacts to infrastructure having severe ecological effects. Failure of sewage treatment plants could lead to increased sewage spills. Increased rainfall could cause major sediment influx to the coastal ocean. Coastal development has reduced the scope for wetland, salt marsh, or estuarine expansion with rising sea level, resulting in major impacts to nursery habitat for many biological resources.

New information to allow people and organizations to better understand the linkage between stresses and climate variability/change.

Change is occurring in the ocean environment off California. Publicity about El Niño has increased public awareness of the role that the ocean-atmosphere system plays in our daily lives. It also serves as an important entree into further educating the public on the kinds of dramatic changes that may occur in the face of more extended climate change. It was noted that El Niño-

induced changes in marine resources and fisheries impacts should be summarized and used to further inform the public.

Win-win coping strategies that will help address the stresses.

Develop resource management systems able to respond to change: Overfishing and excess harvesting capacity of fishing fleets must be dealt with by resource management agencies. It is critical that management develop approaches that can respond rapidly and maintain harvesting capacity consistent with available resources. Management paradigms that lead to sustainable fisheries in the face of environmental uncertainty are needed; the need exists to move from single species management to multi-species or ecosystem management. Adaptive management is one approach, in which management actions are treated as experiments. A new paradigm developing for resource management is the use of harvest refugia, or "no-take zones". This approach addresses many of these problems by protecting some portion of the resource from exploitation. It may be particularly appropriate near the northern end of the range for species that may be expanding in that direction under increasing ocean temperatures.

Socioeconomic effects: In achieving a new balance in harvesting ocean resources, thought should be given to developing new management strategies in conjunction with fishers themselves. It may also be useful to phase new strategies into play in an adaptive way which minimizes socioeconomic disruptions to coastal communities in which commercial and recreational fishing play a significant role, while maximizing our opportunities to achieve true sustainability in the face of regional climate variability and change.

Improve monitoring in the marine environment: Inadequate monitoring of the marine environment leads to an inability to assess the nature and magnitude of environmental change. Improved characterization of physical and biological conditions is required to conduct the research required for a response to changing environmental conditions.

The California Current and Ecosystem Change

The California Current flows generally south along the California coast and is an important element of the marine ecosystem. The US Assessment notes that the strength of the current "is expected to decrease due to the general decrease in atmospheric circulation as a result of a reduction in the west wind drift."[91] Upwelling of colder waters along the coast, an important feature of California's marine ecosystems, may also be altered with climate change.[92]

> The trade winds drive surface waters away from the west coasts of North and South America and these surface waters are replaced by deeper nutrient rich waters, resulting in high levels of primary productivity in these upwelling regions. Factors affecting wind fields therefore will affect the intensity of upwelling. Bakun[93] has argued that increased heating over land could exacerbate the differential between land and sea temperatures, leading to increased local winds

> and therefore increased localized upwelling. In general, heating over land causes increased land/sea temperature gradients during summer months, but the reverse is usually true in the winter. Possible changes in the frequency and intensity of El Niño Southern Oscillation (ENSO) events will also have important consequences for upwelling in the California Current System.[94] The Canadian model shows a steady decrease in the Southern Oscillation Index (SOI; sea-level pressure difference between Darwin Australia and Tahiti). A lower index favors El Niño conditions and therefore more frequent ENSO events are projected under this model. By contrast, the Hadley model shows no clear trend in ENSO events until a quadrupling of atmospheric carbon dioxide concentrations.[95]

Long-term measurements already indicate changes occurring. Field et al. note that changes to marine ecosystems occur more rapidly than others:[96]

> Coastal marine ecosystems can change character much more quickly than California's terrestrial habitats as shifts in climate and ocean circulation redistribute the larvae of invertebrates and fish along the coastline. Many decades of monitoring in the California Current System have revealed a gradual warming of sea surface temperatures as well as a corresponding increase in the dominance of southern species of kelp forest fish and a northward range expansion of sardine populations. In addition to this gradual warming, coastal waters also experienced an abrupt jump in temperatures in the late 1970s that persists. The warmer temperatures of the past two decades have been accompanied by reduced mixing in the water column, reduced upwelling of nutrients, and widespread declines in algal productivity along the California coast. The decline in productivity has been followed by equally large changes in other levels of the food web, including declines of sea birds and an accelerated decline in yields of commercially fished species. Year-to-year variations in temperature and in ocean productivity and accompanying ecological changes caused by the natural El Niño phenomenon parallel those that have persisted since the abrupt temperature rise of the 1970s, but are much shorter lived.
>
> Monitoring of physical and biological characteristics of the California Current dates back many decades at a number of locations.[97] Although the biological data address a limited number of organisms and sites, it is increasingly clear that pronounced changes have also been taking place in marine ecosystems and that these appear to be coupled to climatic shifts.

Oscillations

Oscillations are also occurring in the Pacific Ocean that effect water temperatures. During 1976-1977, California experienced a "large and abrupt shift" in sea surface temperatures.[98] "Zoo-plankton, which feed on the phytoplankton, declined in abundance by more than 70% in parts of the California Current beginning with the temperature shift of 1977.[99] Correspondingly large

declines have occurred in several other levels of the food web, including sea birds,[100] attached algae (which are generally called seaweeds),[101] sea-bottom invertebrates, and fish."[102] Field et al. continue:[103]

> In Southern California, average temperatures increased 2º F above the average of the previous decades. Although the causes of this shift are not fully under-stood, the changes in ocean temperature are associated with a shift in position and intensification of the Aleutian Low Pressure area and its associated westerly winds. Therefore, this persistent warming pattern appears tightly linked to large-scale atmospheric and ocean processes. How it will persist, and whether it reflects human-driven climate change or natural climate variability, is unknown.
>
> Sea surface warming off the coast of Southern California is associated with other widespread physical changes in the ocean that magnify its impacts on ecosystems. Among these physical changes are corresponding increases in stratification of the water column,[104] which decreases the mixing of nutrients from the cooler, deep waters into the shallower waters where life is more abundant. These nutrients are critical for phytoplankton (algae) production in surface waters, and their reduction has led to widespread declines in ocean productivity along the Southern California coast since 1977.[105]

Boesch et al. comment on the impact of changes on commercial fisheries and ecosystems:[106]

> Climate change will have important implications for marine ecosystems that support ecologically and economically important fish populations. As a result of changes in ocean conditions, the distribution and abundance of major fish stocks will probably change substantially. Along the Pacific Coast, impacts to fisheries related to the El Niño/Southern Oscillation illustrate how climate directly impacts marine fisheries on short time scales. Elevated sea surface temperatures associated with the 1997-98 El Niño had a great impact on the distribution and abundance of market squid, California's largest fishery by volume. Landings fell to less than 1,000 metric tons in the 1997-98 season, down from a record-breaking 110,000 tons in the 1996-97 season. Many other unusual events occurred during this same El Niño as a result of elevated sea-surface temperatures. One example is the widespread sea lion pup deaths in California.

Sea Level Rise and Ecosystems

Sea levels are expected to rise around the globe as a result of thermal expansion and increased melting of glaciers and ice. IPCC's Third Assessment report projects a global mean increase in sea level of between 3.5 to 35 inches[107] over the next century.[108] By comparison, since 1850 the level of the San Francisco Bay has increased about 4 inches.[109]

Rising average sea level changes will be particularly noticed in conjunction with storm surges at high tides. Field et al. note that estimate that "with a 12-inch rise in sea level, the current 100-year high in the storm surge felt on the levee system of inland San Francisco Bay and Delta would become the 10-year high—that is, so-called 100-year events would increase 10-fold. Rising sea level could inundate many coastal wetlands, and development in areas such as San Francisco, Los Angeles, San Diego, and other coastal communities may prevent wetlands from migrating inland with the sea. Countless species dependent on estuaries at one time or another in their life cycles and which already suffer from environmental pressures could decline further."[110]

Sea level rise will impact coastal processes. Boesch et al. note that:[111]

> Coastal erosion is already a widespread problem in much of the country and has significant impacts on undeveloped shorelines as well as on coastal development and infrastructure. Along the Pacific Coast, cycles of beach and cliff erosion have been linked to El Niño events that elevate average sea levels over the short term and alter storm tracks that affect erosion and wave damage along the coastline. These impacts will be exacerbated by long-term sea-level rise.

Hector Galbraith et al. has examined the potential impact of sea level rise on shore birds in parts of California. The research provides important insights regarding impacts on wildlife.

Global Climate Change and Sea level Rise:
Potential Losses of Intertidal Habitat for Shorebirds

Hector Galbraith et al.[112]

Global warming is expected to result in an acceleration in current rates of sea level rise, inundating many low-lying coastal and intertidal areas. This could have important implications for organisms that depend on these sites, including shorebirds that rely on them for feeding habitat during their migrations and in winter. We modeled the potential changes in the extent of intertidal foraging habitat for shorebirds at five sites in the United States that currently support internationally important numbers of migrating and wintering birds. Even assuming a conservative global warming scenario of 2oC within the next century (the most recent projections range between 1.4oC and 5.8oC (IPCC, 2001)), we project major intertidal habitat loss at four of the sites (Willapa Bay, Humboldt Bay, San Francisco Bay, and Delaware Bay).

Projected losses typically range between 20% and 70% of current intertidal habitat. Such losses would jeopardize the ability of these sites to continue to support their current shorebird numbers. The most severe losses are likely to occur at sites where the coastline is unable to move inland because of steep topography or sea walls. The effects of sea level rise may be exacerbated by additional anthropogenic factors. In southern San Francisco Bay, for example, sea level rise may interact with land subsidence due to aquifer depletion, and the constraints imposed by existing sea walls on the landward migration of habitat, resulting in the greatest habitat loss. At the fifth site (Bolivar Flats) we project smaller losses as the intertidal habitats are unconstrained by sea walls and will be able to migrate inland in response to rising sea level. Installation of additional coastal protection barriers at this site and others is likely to exacerbate the rate and extent of intertidal habitat loss.

Climate Change and Growth Rates of Vegetation

Various factors affect plant growth including temperature, availability of water, and nutrients including carbon dioxide. Plant growth is also influenced by predators and perturbations including fire. It is not clear how climate change will affect plant communities in California. Field et al. note that climate change will not necessarily increase plant growth. While some factors enhance growth, others may inhibit it. The team notes that, "Climate warming can either increase or decrease plant growth while elevated carbon dioxide spurs it. In California, which factor dominates will depend on the availability of water. Most California plants are highly sensitive to drought, and future changes in the summer dry period are likely to have impacts on plant growth that are at least as large as, and probably greater than, changes in temperature or carbon dioxide."[113]

Increased precipitation may not offset the additional water requirements because of timing. "Increases in winter precipitation may do little to increase summer soil moisture, however, unless a shift in timing extends the rainy season and the period of wet soils. Greater evaporation in a warmer climate is likely to cause greater drying of soils. Thus, summer drought stress may become increasingly important for plant productivity in California, unless the loss of soil moisture can be offset by the water-conserving responses of plants to elevated carbon dioxide."[114] They also note that "higher atmospheric carbon dioxide levels cause *some* plants to be more efficient in their water use. This water-conserving effect has been observed in California annual grasslands,[115] tallgrass prairie,[116] Australian grass-land,[117] and cotton."[118]

Longer-lived plant species will potentially be faced with multiple challenges due to climate change. As Field et al. note, fire, drought, and pests will influence long-term growth patterns:[119]

> Forests may retreat up-slope as well as north, but may not be able to naturally migrate rapidly enough to survive climate change. Pest species will probably adapt to new conditions more quickly, and trees stressed by heat and erratic precipitation will be more vulnerable to infestations. In dying forests, the threat of fire becomes much greater, and intense wildfires may become more frequent, widespread, and destructive. Forests managed for production might be able to shift to new species better adapted to the changed climate. Grasslands might take over thinning forest area, which could be a benefit to grazing livestock, but water availability problems could diminish this benefit. Erosion could accelerate if the intensity and frequency of storms increases while fire removes ground cover and root structures.

Pests

Little research has been done on the potential impacts of climate change and variability on "pests". Pests are loosely defined here organisms that eat, or otherwise negatively impact, plants. Whether warmer conditions and longer frost-free seasons will influence populations of pests or predator-prey relationships that influence pest populations requires further study. As Field et al. note: "Pests and pathogens can play important, even dominant, roles in regulating the

workings of ecological communities, yet only a few studies have assessed the interactions of pests and pathogens with climate change."[120] They note further that: "Many insects can complete their life cycles more quickly under warmer conditions, suggesting that insect pests may become more problematic."[121]

Shaw also notes that further research is needed:[122]

> Very few studies have assessed the interaction of pests and pathogens with a changing climate. This is surprising given the importance of pest and pathogens in structuring ecosystems. Climate change can affect pest and pathogen outbreaks in two ways: 1) warmer temperature may create conditions more favorable for their reproduction and growth and 2) host species may be stressed due changing conditions, making them more vulnerable to attack. In addition, there are a few studies that suggest changes in humidity will increase fungal outbreaks and that decreases in plant tissue quality will decrease pest outbreaks. There have been no definitive studies on this topic but changes in pest and pathogen outbreak may exert considerable control over ecosystem structure.

Stress caused by heat, lack of moisture, and other factors would cause some plant species to become more vulnerable to pests. As Field et al. note: "Pests such as pine bark beetle could be expected to become more prominent or more destructive if climate change stresses their hosts. None of the studies to date have examined what happens when a full suite of predatory insects, parasitoids, and other significant actors in the ecological web are allowed to interact under changed climatic conditions."[123] They comment further that: "Plant pathogens are largely unstudied in the context of climate change. Some researchers suggest that increased plant growth stimulated by elevated carbon dioxide may create a denser leaf canopy that evaporates more water and generates more humidity. A more humid canopy, in turn, could encourage fungal pathogens such as rusts, powdery mildews, leaf spot, and blights.[124] But canopy humidity could also decrease on average, especially if water availability declines or elevated carbon dioxide triggers water-conserving tactics that cause plants to lose less water to evaporation. One study with barley yellow dwarf virus concluded that elevated carbon dioxide made infected plants less sensitive to the infection."

Fog Regimes

Interest in the potential impacts of climate change on fog emerged during stakeholder discussions in various parts of the state. In the Central Valley, "valley fog" is famous for making driving dangerous and flight delays a regular occurrence. To these ecosystems, whether natural or managed, fog is a critical component of the climate. Other parts of California, from the northern coastal forests to central California Coastal valleys are also adapted to fog regimes.

Climate change may alter these patterns through drier conditions or increased wind at certain times, differences in temperature, and ocean current and upwelling changes. Field et al. note that: [125]

> In the north coastal habitats of California, fog is a defining component of the water cycle. Coastal fog and coastal redwoods are partners, with redwoods effectively gathering their summer moisture from the fog. More than 30% of the water reaching the soil and more than 10% of the water annually lost to the air (transpired) by a redwood can come from fog that collects on the leaves and then drips to the soil.[126] If an increase in the frequency of El Niños or a decline in the upwelling of cold water near the coast caused a major decrease in coastal fogginess, the result could be stress and eventual elimination of the coastal redwoods. This remains a subject of great uncertainty. Under some climate change scenarios, coastal upwelling could actually increase and lead to in-creased fog.[127]

Further research on both coastal fog and valley fog regimes is needed.

Desert Ecosystems

Climate change implications for boundary shifts and species distribution and composition was explored at the California workshop in a session co-chaired by Kelly Redmond, Regional Climatologist/Deputy Director, Western Regional Climate Center, and Fred Wagner, Director, Desert Ecology Center, Utah State University.[128]

California Deserts include the regions that get roughly five inches or less of precipitation per year. This area is also affected by climate conditions in nearby wetter areas, because those areas are sources of recharge. The climate there is marginal already. Plants and animals are under a constant state of stress from the austere and demanding climate. Many places are near the limit for all life. Seemingly small changes may move living circumstances from difficult to impossible.

The California portion of the southwest desert receives a greater fraction of its annual precipitation in winter (half or more) than does most of the rest of the desert further east in Arizona and southern Nevada. It thus makes a difference whether precipitation changes happen in the winter or in the summer. The effects of winter increases, for example, would not necessarily balance the effects of equal summer decreases because of the different overhead structure. That is, the efficiency of precipitation in translating to biological or hydrological results is temperature dependent, and in general winter precipitation is hydrologically much more efficient than summer precipitation. Thus, the overhead involved in translating precipitation into runoff, for example.

The climate of deserts is highly variable in time, especially when expressed in relative terms. The drier the climate, the more this is correct. Redmond has looked at the past 102 years of July-June 12-month precipitation for the Southeast Desert Basins Climate Division. The coefficient

of variation (mean divided by standard deviation) is 0.38. For winter (Oct.-Mar.), the corresponding c.v. is 0.46, and for the summer half year (Apr.-Sept.) is 0.56.[129]

Although there is strong interannual variation, there is also considerable variability in decadal means, with 10-year running averages having taken observed excursions of 20-25 percent above or below the long term mean during this same 102 years.

The influence that El Niño plays an important role in the desert. In the winter months it leads to more days with rain, and to more rain per rainy day. La Niña brings the opposite. El Niño and La Niña play a considerable role in explaining the year-to-year variations in climate, to which most certainly all natural biological systems in the region have adapted over the ages, and also probably a role in the decade-to-decade variations.

Because of their low precipitation, small absolute shifts are large percentage shifts. A shift of an inch could be 30-50 percent of the annual total and would also mean a change of several days with precipitation either way.

In general, the drier the climate, the greater the contribution to the annual total that comes from the one or two biggest events during the year. For example, at a moderately dry place (Reno, annual 7.5") the wettest day (out of the 51 annually with measurable precipitation) brings 13 percent of the annual precipitation, on average. At a drier place (Las Vegas, 4.1", 27 days of rain), the wettest day brings 19 percent. At Death Valley (2.3", 17 days), the wettest day brings 25 percent, and at Brawley (3.0", 16 days of rain), the wettest day brings 33 percent.

It should be emphasized that, although water is rare in the deserts, it is the principal agent of change. These are strongly intermittent systems, hydrologically, where nothing much happens for long intervals, and then, wham!, a lot changes in a hurry, perhaps mostly because of a few days, or even hours, each decade or two. Erosive forces become very large for a short amount of time, and then sink back into oblivion. Individual climate events leave their stamp on desert ecosystems for a long time.

The extreme variability makes it that much more difficult to detect long-term change. There also appear to be regimes of behavior, lasting a few decades, that must be factored in when making a determination that something has changed. Single events can influence time series analysis quite strongly. With the very noisy time series, we would like to aggregate (multi-station) records to track climate, but this needs to be done consistently over time, and that subject could afford to be revisited (nationally).

A very large stress on this region is the huge and burgeoning population centers nearby, on all sides (South Coast, Las Vegas, Lower Colorado, Arizona cities, etc.). Cities are further encroaching on fragile desert environments, recreational access is greatly increased, and these areas tend to be treated as something of a playground.

Another important point is that we need to better understand the 20th century climate in a longer context of at least several hundred years. As it turns out, because of their lack of moisture, evidence of past climates is preserved much longer and in more intact form in deserts than in

other climates. Much of our most valuable paleo evidence is from the arid Southwest. Much of this evidence is also more or less in "plain sight", or is found in the bottom lands (the playas, for example), which are most subject to disturbance from the rapidly encroaching population. Thus, important evidence is "at risk" from human disturbance. Possibly, we should be thinking of mechanisms to forestall potential losses, akin to the archeological requirements to survey for irreplaceable cultural artifacts or evidence before large permanent land surface alterations such as developments can proceed. Maybe this idea should be broadened to include past climatic evidence vulnerable to permanent loss.

We do not have high quality and also readily accessible (these are not the same!) information on time trends in important measures of the status of physical, biological and cultural systems. It seems exceedingly difficult to obtain credible information for these regions.

Experts noted that basic understanding of deserts, and especially of their differences (in function, structure, needs, susceptibility to disruption and disturbance) from the rest of the state, probably lags behind the understanding of other regions in California. It appears that some portion of requisite knowledge about these systems, and about what is taking place within them, does exist, but is not readily accessible to a larger audience, who do not know where to go for information.

We have to make sure that we have long term monitoring is in place for the physical, biological and cultural processes that will be most strongly impacted. This in turn means that a long-term commitment to monitoring is absolutely essential, for climate, for biology, for hydrology, and for other related systems. It is thus vital that we keep our long-term monitoring systems intact and healthy. They are constantly threatened with termination and reduction in number and/or quality. This is particularly true for the purely climatic information, but also for biological and hydrological data gathered at university field stations in the region.

Since there was and will always be a desire for more background information about our present climate, it might be helpful to say some things about where such information can be found. I would offer, in this direction, the very

Ecological Surprises

The US National Synthesis team concluded in its key findings that “it is likely that some aspects and impacts of climate change will be totally unanticipated as complex systems respond to ongoing climate change in unforeseeable ways.” It also concluded that “for some systems, the combined effects of climate change and other stresses are very likely to exceed a critical threshold, bringing large, possibly irreversible impacts.”[130]

Shaw reminds us that, “Global changes such as the loss of biodiversity, land use change, land cover change, hydrological disruptions, species invasions, and shifting biogeochemical cycles will interact with a changing climate to alter ecosystems in complex and unpredictable ways. Ecological surprises, extreme and irreversible ecological events, are likely to occur at the nexus of the impacts of climate change and these other significant anthropogenic assaults.”[131]

The following websites provide additional information on ecological health:

Ecosystems and biodiversity: www.wwfus.org/ecoregions/index.htm
Farmland conversion: www.consrv.ca.gov/dlrp/fmmp
Threatened and endangered species: www.dfg.ca.gov/hcpb/species/t_e_spp/tespp.shtmlendangered.fws.gov
Land cover and management www.frap.cdf.ca.gov/projects/land_cover/index.html
Health of Lake Tahoe: www.trg.ucdavis.edu/
List of environmental websites: www.epa.gov/emap/html/olinks.html

Summary

There are a large number of potential impacts to critical natural resource and ecological systems in California. Just as we need to learn more about climate systems and how they may change in regional and local contexts, we also need to learn more about the interactions of natural systems, ecosystems, and socio-economic systems with climate systems.

This section has enumerated a number of important potential impact areas, but it is not comprehensive by any means. As we learn more, it is certain that unforeseen impact areas and surprises will provide new areas of concern and topics for research.

Ecosystems in particular are complex. They provide valuable services, some of which we are only beginning to recognize. Others remain to be discovered. Further research will need to explore both the systems functions within ecosystems, and the interactions between ecological, natural, and human systems.

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Part 3. California's Economy, Society, and Infrastructure, and the Potential Impacts of Climate Change and Variability

Introduction

California's economy and infrastructure are built on natural systems. From tourism to agriculture, the potential implications of climate change and variability are tied to impacts on natural systems. The specific impact areas discussed in this section are therefore linked in important ways to water systems and natural resource and ecological systems discussed in separate sections. The linkage of these potential impact areas makes it difficult to neatly separate the topics for discussion in this assessment. Potential impacts to water systems, for example, will influence virtually every other sector.

This section identifies important elements of the economy and infrastructure that will potentially be impacted by climate change. It also seeks to identify impacts on society and its well-being. All the economic activities and elements that contribute to California's quality of life are not covered in this assessment. Rather, this section represents a sampling of information available at this time. It focuses on frequently asked questions of concern to stakeholders, such as potential impacts to human health. Further research is needed in many areas, and new questions will arise as we learn more.

Infrastructure and Economic Sectors

In July of 2000, California was experiencing rolling power interruptions, high temperatures, and fires. Nothing unusual really, but reminders of existing stresses that may be exacerbated by climate change. Three lanes on Interstate 80 (an 8-lane artery) in the San Francisco bay area buckled due to thermal expansion in a record-breaking heat wave, shutting down the freeway. This was somewhat unusual. At the same time, San Francisco had power interruptions causing BART (Bay Area Rapid Transit) to be out of service for a while. This was also unusual. Both the freeway and BART were quickly fixed. The event was a reminder of the fact that we rely on complex systems, both natural and of our making. What happens when multiple systems fail? At what point are critical thresholds reached?

California relies on a complex set of infrastructure systems for transportation, communications, water delivery, electricity transmission, natural gas and oil delivery, and much more. These systems are interconnected, such that when one fails, others are impacted. Both extreme events and long-term changes in climate will impact these systems. This section reviews some of the potential implications of climate change on selected economic sectors. Due to the limited scope of this assessment, this is not a comprehensive listing of all possible impacts. It draws on scientific research that is on-going and highlights some of the issues that have been identified.

Social and Equity Considerations

The Chief Economist of one of the nation's largest energy utilities observed at the California workshop that the potential social impacts of climate change may fall disproportionately on those at the lower end of the income scale, because their livelihoods are often closely tied to the natural environment.[1]

He noted that for the 20 year period 1978 to 1998, the wealthiest 20% of the population saw a 30% gain in income, but the poorest 20% saw income drop 27%. Only 40% of the population had gains—60% had losses.

Wealthiest	20%	30%	increase in income
	20%	5%	increase in income
	20%	6%	decrease in income
	20%	18%	decrease in income
Poorest	20%	27%	decrease in income

This business economist noted that climate change has the potential to dramatically affect California's economy, but few businesses or government agencies take change into account when forecasting economic trends. Little research has been done on either the business or social implications of climate change.

Fire Risk and Climate Change

Fires in California are dangerous and at times catastrophic. Loss of life and property have been significant.[2] In the past several decades, the loss of hundreds of homes and fatalities in major fires in urban areas including Oakland, Santa Barbara, Malibu, and Laguna Beach have demonstrated the serious toll fires can take. Forest, chaparral, and grassland fires in the Sierra Nevada, the coastal mountains, and elsewhere in the state are an important public safety concern.

Factors contributing to the risk of catastrophic fires include fuel loads (combustible material), high temperatures, dry conditions (low humidity), and wind.[3] These factors are typically present in California in the summer and fall seasons, though they can exist at other times of the year, especially in drought conditions. For example, wild fires in Southern California were occurring in mid-winter of 2002, and a number of serious fires were burning by spring. Some of the major fires in California history have occurred in the winter (see box below).

Analysis by Torn, Mills, and Fried indicates an increase is the number and extent of areas burned by wildfires in recent years, and modeling results under changing climate conditions suggest that fires may be hotter, move faster, and be more difficult to contain under future climate conditions.[4] An added dimension of risk associated with climate change is the potential for heat waves to interact with fire risk. Extreme temperatures compound the fire risk when other conditions, such as dry fuel and wind, are present.[5]

Land-use patterns in California and the development of homes and other structures in fire-prone areas has increased the risk of fire impacts.[6] In many areas of the state, from coastal hills and mountains to the foothills and higher elevations of the Sierra Nevada, development is occurring in areas that are highly susceptible to catastrophic wild fires. Indeed, many of these areas evolved with relatively frequent fire events, and the vegetation is adapted to and reliant on fire.[7]

A California Coastal Commission study provides a useful account of fire history in the Los Angeles area:

Wildfire Hazards Survey in the California Coastal Zone[8]

Troy Alan Doss
Report to the California Coastal Commission

In the Wildfire Safety Panel report to the Los Angeles County Board of Supervisors, the County Fire Department provides a history of wildland fires in the Los Angeles basin. This history can be applied to many other communities of California, and it reads as follows:

Less than one percent of all wildfires escape early control. It is that fraction of a percent that is responsible for the most damaging fires. In Los Angeles County there have been more than 20 catastrophic wildfires since the beginning of organized fire protection. The Los Angeles County Fire Department experienced their first urban interface fire long before the term was ever invented. On a windblown evening in December 1927, a fire in the La Crescenta Valley roared up and over the Verdugo Mountain range and destroyed more than 100 homes. That fire was the first of many that would mold and shape our current fire restrictions, codes, and fire suppression tactics.

It was not unexpected when the Kinneloa Fire in the Altadena area and the Old Topanga Fire of Malibu exploded into Firestorm '93. These areas had burned before, as had nearly every square mile of the brush-covered areas of the county since 1919. The Kinneloa Fire destroyed more homes (121) along the foothills of the San Gabriel Mountains than had previously been destroyed. Previously, the worst fire occurred at the mouth of the San Gabriel Canyon in November 1980 destroying 55 homes. In the past 60 years, a dozen fires have destroyed 332 homes along the front country of the San Gabriel Mountain range. As bad as that is, it pales in comparison to the fire history of the Santa Monica Mountains.

It is in the Santa Monica Mountains range where fires have crisscrossed the terrain so often that some residents not only have lost one home, but some sadly have lost three after rebuilding on the same site. The Santa Monica Mountains are a true design for disaster. In the fall and early winter months, as if on a regular schedule, strong Santa Ana winds howl through the canyons and out to sea and the relative humidity plummets to single digits. After the long hot summer has taken its toll on chaparral, often stressed by repeated droughts, the winds set the scene for disaster. Once a fire gains a foot-hold, with Santa Ana winds blowing, it is virtually impossible to contain until the wind abates or it runs into the sea. The fires historically follow well-defined wildfire corridors. When large and damaging fires occur you'll find the wind and fire corridors perfectly aligned.

When fire roared down Old Topanga Canyon in November of 1993, it destroyed more homes than any previous fire in the history of the Los Angeles County Fire Department. The Malibu Fire in October 1978 was the worst previous fire, laying waste to thousands of acres and 230 homes. The Old Topanga Fire destroyed 369 homes and resulted in the deaths of three civilians. The fire traversed a total of seven previous burns through brush that was as young as eight and as old as 70 years. It had been eight years since the last major fire.

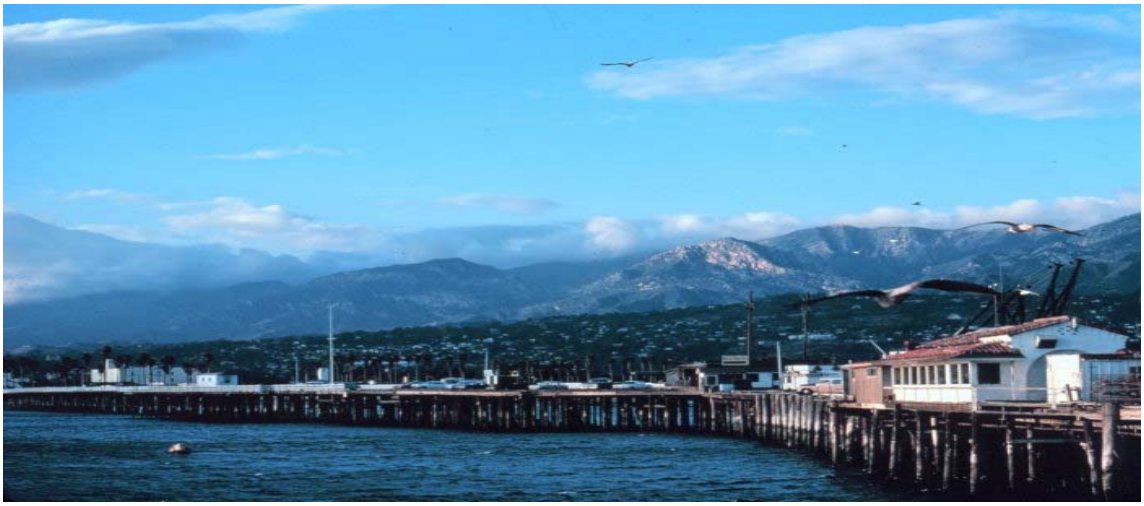
Since 1927, a total of 24 wildland fires have caused the loss of 1,502 homes, 830 other structures, 271,047 acres and five fatalities. Previous fires include the 1985 Malibu Fire, 1982 Dayton Fire (85 homes destroyed), and the 1970

Malibu Canyon Fire (103 homes destroyed). The 1993 Old Topanga Fire burned much of the same area covered in the 1970 burn. The last time Topanga Canyon had seen a damaging fire was December 1958 when 74 homes were reduced to rubble. Between 1938 and 1943, three fires destroyed more than 600 structures in the Topanga Canyon area.

In addition to impacts to structures and public safety, fires disrupt important infrastructure elements. The high-voltage transmission grid, for example, is affected by wildfires. Voltage levels must be reduced when carbon builds up as a result of the fire. Lower voltage distribution systems with wood poles are also vulnerable to fire. Some communications installations are also vulnerable to fire.

There is an important link between fire events and erosion processes. Fires cause certain soils to become "hydrophobic" or water repellent. This leads to accelerated runoff and erosion during rains that follow the fire.

Coastal Impacts on Structures and Infrastructure



Impacts from climate change and variability will affect a significant economic and environmental resource in California. A 1997 US EPA study found that in the San Francisco Bay area alone, tourism has been estimated to generate over $4 billion a year.[9] NOAA reports that coastal tourism is the second largest employer in the US.[10] The coastal sector assessment notes that:

> Oceans, bays and beaches are among the most popular tourist destinations in the nation, surpassing even national parks and historic sites in terms of their visitation. As many as 180 million people visit the coast each year for recreational purposes in all regions of the country, and many regions depend upon tourism as a key economic activity.[11]

Stormy, turbulent seas and intense precipitation events under existing climate conditions can cause extreme erosion along California's coast. Coupled with sea level rise and more extreme precipitation, roads, railroads, homes, and other structures and infrastructure will be threatened. The Pacific Coast Highway in parts of California is besieged by mudslides and high waves even during mild winter storms. Legendary Highway 1 from Cambria to Carmel suffers washouts nearly every year, some closing the road for months. Future erosion occurring more frequently could close it permanently if it becomes too costly to maintain. Roads throughout California are affected by mud and rock slides each winter. Coastal rail routes experience the same problems during heavy storms, sometimes shutting down passenger and freight traffic for days.

The coastal sector report provides the following characterization of the geology of the California coast and its susceptibility to erosion:[12]

> Mainland shoreline systems of the U.S. West Coast border an active tectonic region of fault-bounded crustal blocks with high elevations. Ancient shoreline terraces hundreds of meters above present sea level are evidence of rapid and extensive crustal uplift along the coasts of Southern California. The relatively narrow offshore continental shelf is bordered by deep ocean basins, and in several areas submarine canyons extend almost to the shoreline itself. Eroding headlands and sea cliffs provide much of the sediment to feed adjacent beaches. Rivers too, often fronted by extensive lagoons or bays, have historically provided much of the sediment to the nearshore system. However, extensive damming of streams and rivers for flood control and irrigation has greatly reduced the volume of material reaching the coast. The mainland beaches are relatively steep, producing a narrow zone where the brunt of the forces generated by breaking waves are concentrated. Climate variability, such as the El Niño Southern Oscillation (ENSO), affect the frequency and intensity of storms impacting this narrow zone, with corresponding cycles of beach and cliff erosion. During the 1982-83 and the 1997-98 El Niño events, impacts were especially severe along shorelines throughout California, Oregon and Washington.[13]

Homes in California are damaged and destroyed during erosion accelerated erosion events.

Source: The Potential Impacts of Global Warming on Our Coasts and Oceans: Critical Findings for Coastal Areas And Marine Resources From The First National Assessment of The Potential Consequences of Climate Variability and Change

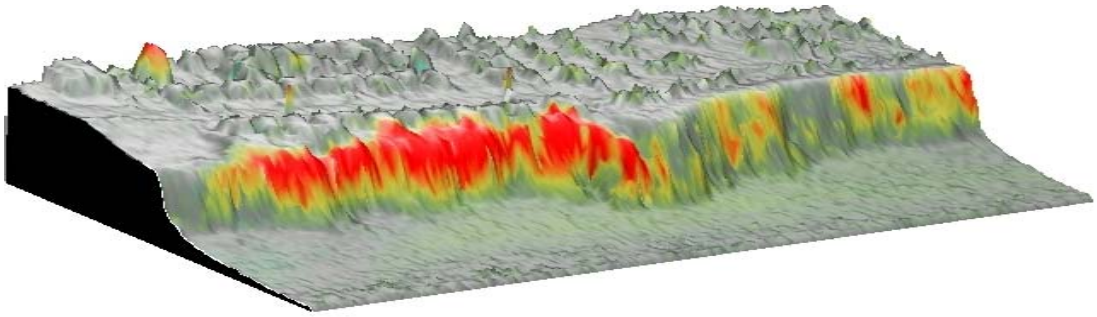
The following images from a NASA project indicate some of the scientific tools that are being applied to map and measure the impacts of coastal erosion processes.

NASA Survey of 1997-8 El Niño Erosion

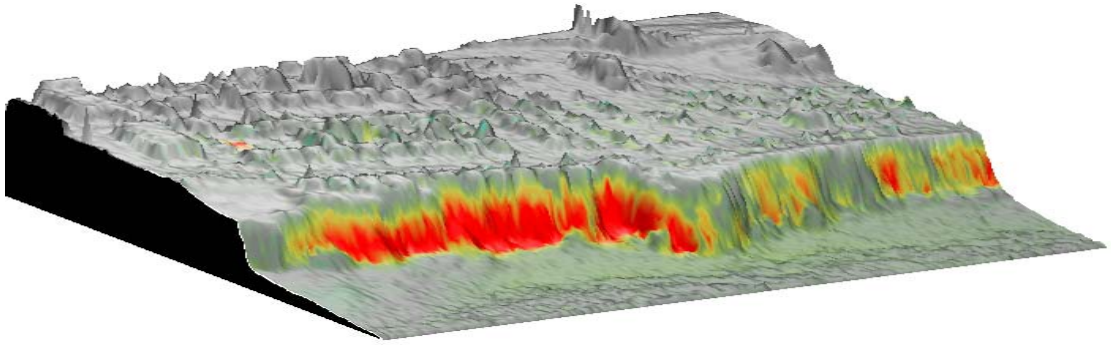
Pacifica, California[14]

NASA's Airborne Terrain Mapper (ATM) collects 3,000 to 5,000 spot elevations per second as the aircraft travels over the coast at approximately 150 feet per second. Using the ATM and a Global Positioning System (GPS) satellite receiver, researchers have been able to survey the beach elevations to an accuracy of four inches. The before and after images indicate erosion along the coast in this location.

April 1998 USGS photo



Oct 1997, ATM survey colored by winter's elevation change



April 1998, ATM survey colored by winter's elevation change

The coastal sector assessment report notes that both the Hadley and Canadian models indicate increases in runoff in parts of California:[15]

> For the Pacific coast, both climate model models suggest increases in the runoff, especially in southern California. Results indicate that there will be an increase in the number of storm events entering the U.S. from the Pacific, due to a deepened and southward-shifted Aleutian Low and a southward-shifted jet stream.[16]

Extreme rainfall events have increased over the last century for the US as a whole, and they are likely to become more common, as may droughts and floods.[17] However, the models do not provide a clear picture with regard to precipitation patterns in California. As Boesch et al. note:[18]

> In contrast to a relatively high degree of confidence associated with the increases in global temperature that are associated with global change, the effects upon hydrological cycles are considerably less certain, particularly on regional scales. The scenarios generated by the Canadian and Hadley models in particular are often contradictory as to trend.[19]

Economic Impacts on Coastal Resources and Systems

California derives important economic benefits from coastal resources in a number of ways.

> Coastal and marine ecosystems support diverse and important fisheries throughout the nation's waters, hold vast storehouses of biological diversity, and provide unparalleled recreational opportunities. Demands on coastal and marine resources are rapidly increasing, and as coastal areas become more developed, the vulnerability of human settlements to hurricanes, storm surges, and flooding events also increases.[20]

Population growth in coastal areas has increased pressure on ecosystems. As the coastal sector report notes, "the list of ongoing stresses to coastal environments is very long and growing": [21]

> The Environmental Protection Agency estimated that nearly 40% of the nation's surveyed estuaries are impaired by some form of pollution or habitat degradation.[22] Some 30 to 40% of shellfish growing waters in the nation's estuaries have harvest prohibited or restricted each year, primarily due to bacterial contamination from urban and agricultural runoff and septic systems (Alexander 1998). Additionally, over 3,500 beach advisories and beach closings occurred in

the United States in 1996, primarily due to storm-water runoff and sewage overflows.[23] Population pressures and land and resource uses farther inland also have detrimental impacts on coastal resources. Effluent discharges as well as agricultural runoff have caused significant nutrient over-enrichment in many coastal areas. Dams, irrigation projects and other water control efforts have further impacted coastal ecosystems and shorelines by diverting or otherwise altering the flow of water, sediments and nutrients.

Potential Impacts of Sea Level Rise

Sea level rise may have widespread impacts on California. Coastal structures from harbors to houses will succumb to the ocean, as numerous California beachfront homes did in February 1998. Beaches and wetlands will be flooded. Agricultural lands in the Sacramento-San Joaquin Delta, some already as much as 25 feet below sea level, may be permanently lost. As the ocean encroaches, some aquifers near the coast could become contaminated by saltwater intrusion. Today, sewage systems in some coastal communities are overwhelmed by storm runoff and high tides, and the problems could become much more serious as sea level rises.

Many coastal airports are vulnerable to flooding. Built on wetlands back when they were called swamps, many of these facilities, such as the San Francisco, Oakland, and Santa Barbara airports, are about 10 feet above current average sea level. Extreme high tides, coupled with flood conditions, can reach close to the existing levels. A recent tidal flux in the San Francisco Bay area closed Highway 101 north of the city due to eight-foot tides, two feet above what had been expected. With an additional meter of sea level, a number of critical facilities would be highly vulnerable. In the future, sea level rise, storm surges, and high tides could conspire to inundate runways. Harbors may suffer wave damage, additional siltation from storm runoff, and other navigation and safety problems. Jetties and seawalls may have to be raised and strengthened to protect harbors, which support commercial shipping, recreation, tourism, and many other economic sectors.

El Niño and Storm Surge Impacts

Westerling provides an interesting analysis of the combined effects of El Niño, storm surges, and sea level rise in the box below.

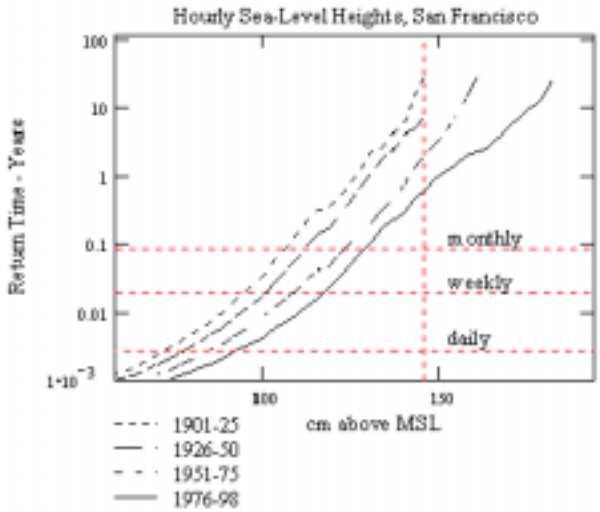
El Niño and One Hundred Years of Storm Surge in the Eastern North Pacific[24]

Anthony Westerling

The Intergovernmental Panel on Climate Change (IPCC) estimates that global mean sea levels have risen 10-25 cm in the past 100 years, and projects a further rise of 50 cm by 2100.[25] The sea-level records from three of the NOAA tide stations used in this analysis–San Diego, San Francisco, and Seattle–indicate a sea-level rise of roughly 20 cm this century. This is somewhat smaller than either the maximum storm surge or the variation due to tides experienced on the U.S. West Coast.[26] For example, the maximum storm surges recorded at San Francisco can exceed 60 cm, while the maximum sea-level variation off the California coast due to tides is nearly five times larger.[27] El Niño events can also elevate monthly mean sea levels by up to 30 cm or more off the California coast. Storm surge here refers to the "local, instantaneous sea-level elevation that exceeds the predicted tide and which is attributable to the effects of low barometric pressure and high wind associated with storms...excluding the effect of waves."[28]

When extreme high tides, storm surges, ENSO-related sea-level increases and long-term sea-level increases come together, the results can be costly. This is what happened during the 1982-83 El Niño, when elevated sea-levels from winter storms resulted in more than $100 million in damages to coastal property in California, in addition to losses from high winds and intense precipitation.[29] Flick and Cayan (1984) note that this was a relatively rare event in that large storm surges coincided on three separate occasions with high tides near a four-year maxima in the monthly mean high tide, on top of a sustained sea-level elevation associated with strong El Niño conditions. By comparison, Flick (1998) finds peak storm surges and wave sizes in California set new records in 1998, but did not coincide with extreme high tides, and damages were reduced.[30]

Clearly, any changes in the frequency and intensity of the largest winter storms, or in their tendency to coincide with ENSO-related fluctuations in mean sea level, could be as or more important than the IPCC's anticipated rise in mean sea levels in determining the risk of damage to coastal property. Consider the historical sea level height frequencies for San Francisco. These frequencies are computed for hourly sea level heights for San Francisco for four roughly equal periods spanning 1901-98. The right tails of these distributions correspond to winter storm events.



Despite a small trend in annual winter storm frequency for San Francisco, the pre-1926 maximum of 143 cm above mean sea level (MSL) is exceeded for a total 36 hours, corresponding to15 separate winter storm events, after 1975. All but one of these storms occurred when sea levels were elevated due to an El Niño event. De-trending these samples and projecting them onto an annual sea level rise of 3.5 mm/year for 2001-25 indicates an annual frequency of 2.5 to 5 hours a year in which the pre-1926 maximum sea-level is attained or exceeded.[31] This is an increase of between 62 and 124 times for the return time for the pre-1926 maximum. If future climate change results in changes in storm frequency and the inter-annual variability in sea level and storm frequency, the impact on coastal infrastructure may be far different from what we would anticipate based on long term sea level rise alone.

Impacts of Sea Level Rise on Coastal Aquifers

Randy Hanson and Mike Dettinger examined the potential implications of sea level changes on a coastal aquifer north of Los Angeles. The analysis looks specifically at the potential impact of changing sea levels on coastal groundwater systems.

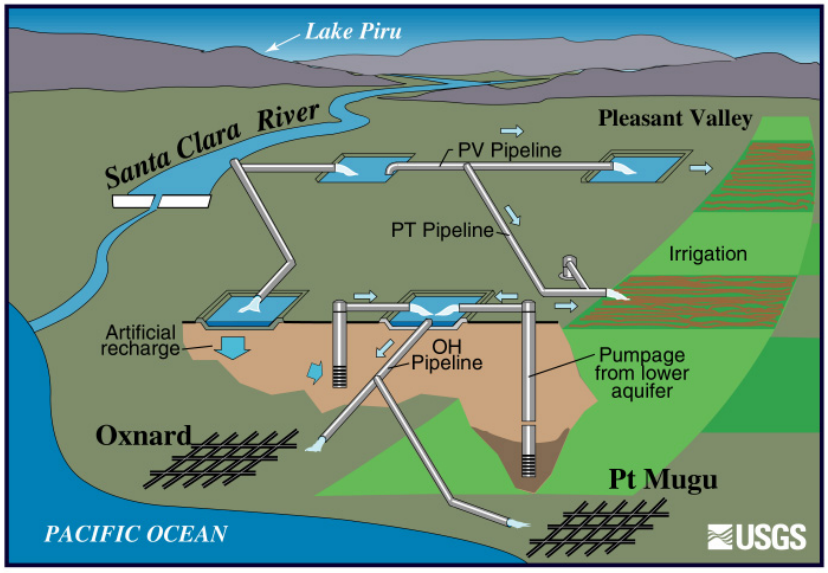
Water Resources in the Ventura Basin[32]

Randy Hanson, US Geological Survey - San Diego District
Mike Dettinger, US Geological Survey - San Diego District, and
Climate Research Division, Scripps Institution of Oceanography

CAP is working with selected agencies to develop, assess, and incorporate long-lead climate forecasts into California's water resources and hazards management processes. A requirement of water-resource agencies all around the Sierra Nevada is development of seasonal-scale forecasts and strategies for managing the April through July (or September) streamflows in their respective rivers and into their respective reservoirs. Elsewhere in the State, ground-water aquifers are used as important components of water-supply systems. In these settings also, long-lead seasonal forecasts of climate, runoff, and ground-water recharge are key to improved decision-making and management of the State's (usually overstressed) water resources.

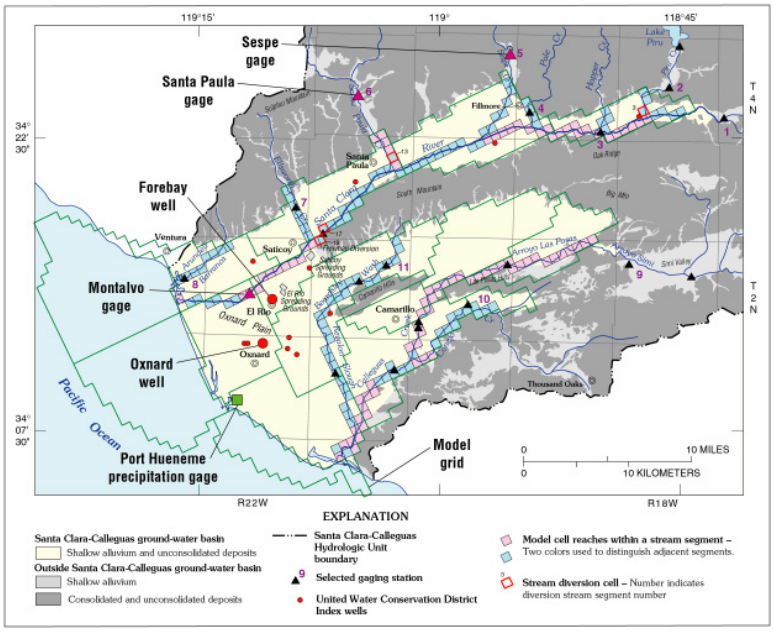
In southern California, CAP members Randy Hanson and Mike Dettinger are carrying out simulations of ground-water/surface-water responses and management. These simulations, for the Santa Clara-Calleguas Basin, Ventura County, California (1950-1995), are forced by 45-yr ensembles of global climate model hindcasts. The Santa Clara-Calleguas region is depicted below.

Santa Clara-Calleguas Water Resources

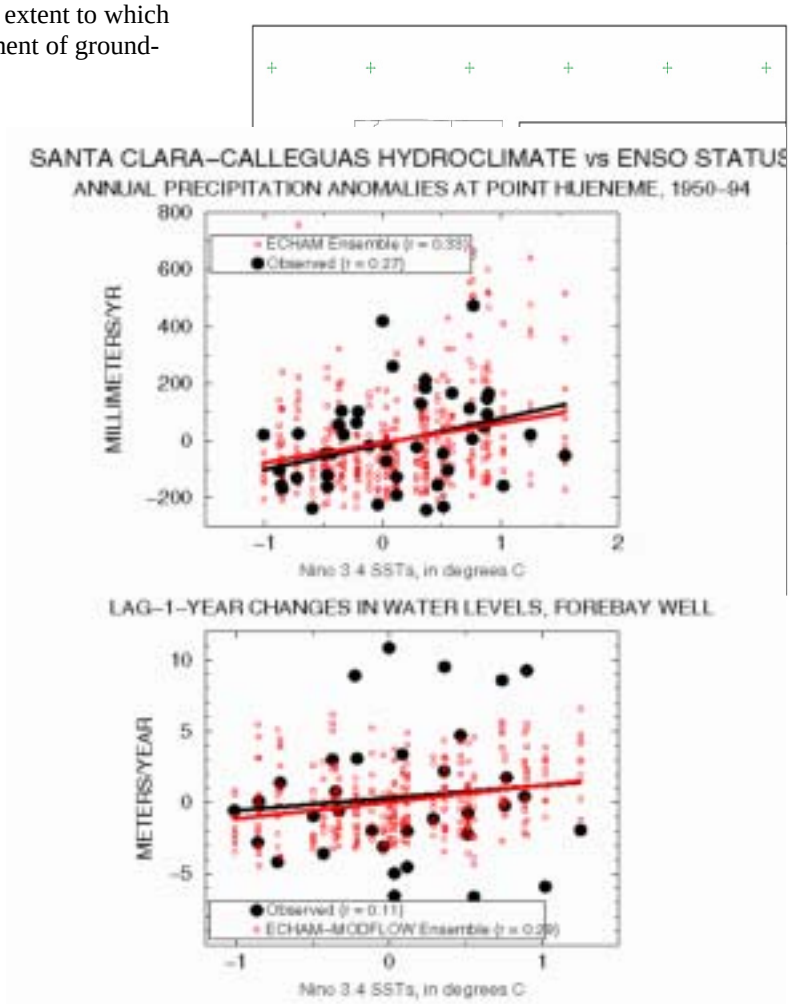


The USGS developed the ground-water/surface-water model for the United Water Agency of Ventura (depicted below) during the 1990s and it is used to address management issues concerning the impacts of ground-water and surface-water developments and usage in various parts of the basin.

Santa Clara-Calleguas Ground-water/Surface-water Model



CAP is coordinating uses of this model with United Water and, more recently, Ventura County and the Fox Canyon Ground-water Management Area, in order to design our efforts and experiments to address the most recent management issues. Climate variations influence ground-water and surface-water systems to differing extents. The overall extent of climatic influences in a coupled ground-water/surface-water system can be difficult to guess and depends on how closely the ground-water and surface-water systems are coupled, on which system dominates the year-to-year hydrologic variations in a basin, and on the time scales and avenues by which the climate forcings enter the particular hydrologic systems. Thus the extent to which climate forecasts will be useful in management of ground-water/surface-water systems is uncertain.



Working with the local management agencies, in order to explore the applicability of climate simulations and forecasts in management of the ground-water/surface-water system of this typical West Coast coastal basin, ensembles of hindcast climate simulations from 1950 to 1998, by three different climate-prediction model runs provided by IRI, have been used to force a calibrated model of ground-water/surface-water conditions in the Santa Clara-Calleguas basin of southern California. The image above shows the scale relationship between the climate model and the Santa Clara-Calleguas ground-water/surface-water model. Comparison of the responses simulated with the hindcast fields with historical observations and calibrated simulations of ground-water and surface-water variations in the basin indicate that current climate simulations (and, perhaps, forecasts) reproduce at least some of the longer term forcings to which the ground-water/surface-water systems respond on interannual time scales. The simulations show that the combined climate-model/surface-water/ground-water simulations reproduce the most basic responses of the Santa Clara-Calleguas basin to global climate as forced by the AMIP sea-surface temperatures; that is, the same time scales of variability (QBO, ENSO, and decadal) are traceable from the SST forcings through the simulated Californian precipitation totals through the simulated streamflow and pumpage into the simulated ground-water levels. Furthermore, the magnitude of the mean ground-water responses to the historical range of tropical sea-surface forcings is entirely realistic.

The figure above summarizes how the climate ensembles respond to the tropical sea-surface temperatures that are used to force a climate model (top panel) and how, in turn, the ground-water/surface-water model responds to those climate simulations (bottom panel). The top panel shows that on average (by the regression lines) the ECHAM (climate) model tends to do a good job of returning the observed variation of precipitation over Ventura as a function of imposed tropical forcings (that is, the regression lines lay over each other about as well as anyone could hope). The ECHAM ensemble precipitation members are also observed to have about the same scatter as the observations around the central precipitation tendencies. So it would appear that the ECHAM simulations of precipitation in this case are a reasonable representation of how variable precipitation over Ventura is, both due to ENSO and other "random" variations.

Once the simulated precipitation is used to force the surface-water/ground-water model, the response of the ground-water levels (shown in the bottom panel) can be assessed in much the same way. As with precipitation, the "mean" ground-water level changes in response to various tropical forcings (as indicated by the regression lines) are very similar. Thus the "expected" value of ground-water level response (as a function of tropical forcing) is well simulated by the coupling of climate/ground-water models. The scatter around those expected values are, however, much smaller in the simulation than in the observations. This suggests that somewhere in the process, sources of variability have been neglected or underestimated. The top panel indicates that the climate model is not under-representing the precipitation scatter, so that it appears that the current simulations are either underestimating the precipitation effects on the ground-water system (we believe that this could be an underestimation of how much pumpage changes with precipitation), or that other non-precipitation-forced variations, not represented in the model, are missing (like changes in management styles and land uses), or--most likely--that both of these problems are limiting the simulated variability of ground water as a function of tropical forcing.

Initially though, CAP is interested in how well the mean response can be forecasted. In ensemble forecasts of the ground-water responses to forecasted tropical forcings, the results above suggest room for much optimism: the coupled climate/ground-water model system reproduces the historical "mean" ground-water responses remarkably well. The deficit of residual variability around these mean responses in the ground-water ensembles mostly will limit the amount of ensemble ground-water scatter in a forecast and not the mean forecasted ground-water response to a given season's (forecasted) weather. CAP hopes to improve the simulated scatter in order that the uncertainties in such forecasts can be realistically represented and applied in decision-making processes.

Forecasts by such methods are thus most immediately limited by the skill of current long-lead precipitation forecasts. The next steps are to resimulate the responses with seasonal, rather than annual, precipitation forcings, and to explore more complex forms of downscaling since the present simulations use precipitation rates directly from the climate models.

Fisheries

California's commercial and recreational fisheries are important and valuable economic sectors. Nation-wide, "the oceans and coastal margins provide unparalleled economic opportunities and revenues."[33] As the California Department of Finance notes, however, over-fishing has long been a problem:

> By 1940 California was a leading fishing state because of the sardine industry. Between 1914 and 1929, an average of 300 million pounds of sardines were caught each year. Sardines were used for fertilizer, fish oil, salmon bait and other products. By 1910 Monterey was the canning capital of the world… In fact, sardines were being over fished and in the late 1930s the catch began to dwindle. In 1967, a fishing moratorium was declared.[34]

Over-fishing is a serious problem globally, and many of California's commercially fished species are already in decline.[35]

> Catastrophic fish population collapses and economic disasters have struck most regions of the country. For example in January 2000, the West Coast groundfish

> fishery joined the New England groundfish fishery in being declared in serious trouble by the Secretary of Commerce. Such fishery collapses have dramatic impacts to both marine ecosystems and the coastal communities which have long been dependent upon these marine resources.[36]

Climate change will likely impact economically important fisheries. Boesch et al. found that:[37]

> Climate change will have important implications for marine ecosystems that support ecologically and economically important fish populations. As a result of changes in ocean conditions, the distribution and abundance of major fish stocks will probably change substantially. Along the Pacific Coast, impacts to fisheries related to the El Niño/Southern Oscillation illustrate how climate directly impacts marine fisheries on short time scales. Elevated sea surface temperatures associated with the 1997-98 El Niño had a great impact on the distribution and abundance of market squid, California's largest fishery by volume. Landings fell to less than 1,000 metric tons in the 1997-98 season, down from a record-breaking 110,000 tons in the 1996-97 season. Many other unusual events occurred during this same El Niño as a result of elevated sea-surface temperatures. Examples include widespread sea lion pup deaths in California, catches of warm-water marlin in the usually frigid waters off Washington State, a series of anomalous plankton blooms, seabird die-offs along the Aleutian Islands, and poor salmon returns in Bristol Bay, Alaska. With few exceptions, the potential consequences of climate change are not yet being considered in a management context, despite the fact that it has been shown that planning protection or retreat strategies for coastal developments can substantially reduce the economic impacts of inundation and shoreline migration.

Ocean currents are also expected to change as a result of climate change. These changes will affect coastal processes and ecosystems.[38]

> In the Pacific, the strength of the California Current is expected to decrease due to the general decrease in atmospheric circulation as a result of a reduction in the west wind drift.[39] Changes in the strength of the Aleutian low pressure system have been linked to regime shifts in the North Pacific.[40] Intensification of this low pressure system is linked to an increase in wind stress and an increase in surface water temperatures in coastal regions of the Northeast Pacific. These changes have important implications for biological production in these regions
>
> The second major consideration for wind-driven processes involves intensity of upwelling and downwelling processes. The trade winds drive surface waters away from the west coasts of North and South America and these surface waters are replaced by deeper nutrient rich waters, resulting in high levels of primary productivity in these upwelling regions. Factors affecting wind fields therefore will affect the intensity of upwelling. Bakun has argued that increased heating

> over land could exacerbate the differential between land and sea temperatures, leading to increased local winds and therefore increased localized upwelling.[41] In general, heating over land causes increased land/sea temperature gradients during summer months, but the reverse is usually true in the winter. Possible changes in the frequency and intensity of El Niño Southern Oscillation (ENSO) events will also have important consequences for upwelling in the California Current System.[42] The Canadian model shows a steady decrease in the Southern Oscillation Index (SOI; sea-level pressure difference between Darwin Australia and Tahiti). A lower index favors El Niño conditions and therefore more frequent ENSO events are projected under this model. By contrast, the Hadley model shows no clear trend in ENSO events until a quadrupling of atmospheric carbon dioxide concentrations.[43]

Climate change will also impact coastal processes through changes in freshwater flows to estuaries, bays, and the ocean.[44]

> Freshwater runoff affects coastal ecosystems and communities in many ways. The delivery of sediment, nutrients and contaminants is closely linked to both the strength and timing of freshwater runoff. Salinity gradients are driven by freshwater inputs into estuaries and coastal systems, and have strong effects on biotic distributions, life histories and geochemistry. Coastal runoff also affects circulation in estuaries and continental shelf areas; and increases in runoff have the potential to increase the vertical stratification and decrease the rate of thermohaline circulation by adding more fresh water to the system.
>
> Changes in freshwater runoff will also result both from climate-related factors and changes in human population, land-use, and consumption and diversion.[45]

Boesch et al. examined the potential impacts for San Francisco's Bay and delta estuary as follows:

Freshwater Flows to the San Francisco Bay/Delta Estuary[46]

Donald F. Boesch, John C. Field, Donald Scavia, Eds.
The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources

The San Francisco Bay and the Sacramento/San Joaquin Delta region comprise one of the United States' most significant and highly studied estuarine systems. This system has a surface area of nearly 400 square miles[47], a length of over 60 miles[48] and it is the focus of one of the largest population centers in the United States. Like many estuaries, San Francisco Bay supports a complex and delicate variety of ecosystems, while serving as an invaluable resource for the humans who live around it. A significant portion of California's freshwater supply is diverted from the upstream watershed and from the Sacramento/San Joaquin Delta in the upper reaches of the system into the elaborate plumbing system that stores and channels the state's water.

Fishes of high economic importance, as well as hundreds of species of flora and fauna, some of them endangered, depend upon the estuarine ecosystem for their survival. As a balance between the land and ocean environments, the estuary is sensitive to changes in both its upstream watershed and the outside Pacific Ocean. Already, the Delta and the Bay have been stressed by numerous impacts, often relating to human activities. The region has also been subject to numerous ecological insults, including an extraordinary number of invasive species. The Bay and Delta have been described as "the most heavily invaded estuary in the world", with nearly 200 non-native species documented.[49] In some parts of the estuary, non-native species account for as many as 90% of the species and 97% of the total biomass.

The San Francisco Bay consists of two relatively distinct sub-estuaries, the South Bay and the Central/North Bays. The Bay's total volume of about 1.6 cubic miles[50] equals about one-third of the freshwater runoff that enters the Bay annually, mostly through its northern reach at the confluence of the Sacramento and San Joaquin Rivers.[51] The estuary's sole connection with the open ocean is through the Golden Gate, where relatively freshwater flows seaward near the surface and the more saline waters of the Pacific flow landward through a deep channel. The defining process of the estuarine environment is this mixing of saline ocean water with fresh river water. As sea-level determines the level of the estuary and therefore its horizontal boundaries, the potential for rapid sea-level rise has tremendous implications for the estuary and the humans who depend on it. Freshwater inflow to the estuary, both in terms of its volume as well as its timing, is the other major factor which determines salinity distributions in the Bay/Delta, a factor which is likely be strongly affected by climate change.

Freshwater Inflow

California receives an annual average of nearly 60 cubic miles[52] of fresh water in the form of rain and snow. Of this, about 40% ultimately becomes streamflow in the state's river network, most of which culminates at the Delta of the Sacramento and San Joaquin Rivers at the head of the San Francisco Bay. This freshwater supply is highly managed to ensure adequate supplies throughout the year. While most of this water originates in the northern third of California, a substantial portion is collected in reservoirs during the rainy season for later conveyance to the areas of greatest demand in Central and Southern California. Storage capacity in the Sacramento/San Joaquin drainage amounts to approximately 8.6 cubic miles.[53]

The northern reach receives over 98% of San Francisco Bay's freshwater input through the Delta of the Sacramento and San Joaquin Rivers. Runoff from winter storms collects over approximately 60,000 square miles[54], an area comprising nearly 40% of the state of California.[55] Sacramento River flow is dominated by direct runoff from storms over the western slopes of the northern Sierra, while San Joaquin River flow is primarily due to the melting of accumulated snowpack in the southern Sierra. This leads to a difference in the timing of the peak flow in the two rivers. Since the peak in the Sacramento River flow is associated with direct runoff from storms, it coincides with the winter/spring rainy season.[56]

The greater elevations of the southern Sierra mean that much of the precipitation there is retained as snowpack until temperatures rise enough for melting to occur, usually in late spring and early summer. As this water flows through the valley, some is lost to seepage into underground reservoirs, some to evaporation, and a large portion is dammed and used for municipal supplies and irrigation. When the remaining flow reaches the Sacramento/San Joaquin Delta, it is subject to further reductions. The primary diversions are the State Water Project which pumps fresh water from the Delta to supply Southern California with much of its water; the Central Valley Project which supplies water primarily for irrigation; irrigation canals on the Delta islands; and several local canals providing industrial and municipal supplies.

The high freshwater input from the Delta causes a large along-estuary salinity gradient through the North and Central Bays.[57] When flows are at their peak, the freshwater signal overrides the up-estuary salt flux and the entire northern reach rapidly becomes fresher. As flows subside, tidal mixing and estuarine circulation begin to dominate, slowly pushing the more saline water up the estuary. This cyclic tug-of-war between saline and fresh conditions engenders a gradation of ecosystem types from marine near the Golden Gate to riparian upstream of the Delta. The actual formation and survival of these ecosystems is influenced and limited by human development around the estuary, in combination with year-to-year variability in the freshwater supply. This can be particularly important for the estuary during the dry season, when controlled releases of stored fresh water are used to flush saltwater from the Delta region and the San Francisco Bay.

Implications of Climate Variability and Change

Variations in the timing and amount of the freshwater supply have significant impact on California and such effects are harbingers of potential effects of longer-term climate change. Excessive rainfall in a short period can overflow reservoirs and cause severe flooding, as in the storms of January 1997. Conversely, insufficient total precipitation during a given rainy season can lead to freshwater shortages later in the year, potentially leading to water rationing, losses of agricultural and hydroelectric power commodities and other statewide impacts. Low freshwater flow due to drought and excessive upstream diversions can lead to unnaturally high salinities in the Bay/Delta estuary, potentially contaminating freshwater supplies and adversely impacting the health of the estuarine ecosystem.[58]

Interannual and interdecadal variations are also of strong significance. Multi-year events such as the drought of 1987-1992 have cumulative effects on economies and ecosystems. A multi-year drought or flow abundance can alter salinity, creating conditions unsuitable for existing estuarine ecosystems. Confounding this situation further is the extensive human development around the Bay/Delta which prevents ecosystems from migrating upstream or downstream to more suitable salinity regimes, leading to intensified ecosystem degradation or loss.

The potential implications of global warming for freshwater flows in the Bay/Delta watershed are somewhat uncertain. In particular, it is unclear whether overall water supply will increase or decrease. Several climate models do suggest that precipitation will increase, although much of this increase is likely to occur in intensive precipitation events resulting from winter storms. It is also unclear what the overall effect of global change on interannual and interdecadal variability may be, although it is clear that increased temperatures would lead to a shift of freshwater flows from spring to winter. This is due to the earlier melting of snowpack under warmer conditions. In fact, this effect has already been observed. A slow rise in winter temperatures since the 1940's has led to earlier snowmelt runoff,[59] effectively decreasing the natural storage in the Sierra on an interdecadal time scale. This has partially contributed to an overall rise in Bay/Delta salinities over this period.

If this effect were to strengthen significantly over the next century, the results could be dramatic. Increased winter flows and decreased spring flows would allow contaminants (e.g., pesticides, urban pollutants, etc.) to accumulate more during the longer dry season. When the high winter flows finally arrive, they would flush the system quickly, potentially resulting in a much higher concentration of pollutants which could damage ecosystems and contaminate freshwater supplies. Additionally, the decreased natural storage would make repulsion of saline waters from freshwater pumping sites more difficult, as freshwater supplies during the dry season would be considerably reduced.

Finally, a shift toward earlier flows would result in much fresher salinity distributions in the wet season and much more saline waters in the dry season. This change in the estuarine salinity environments would have significant effects on all estuarine ecosystems, though the details of such changes are as yet poorly understood. Freshwater flows would arrive earlier due to decreased snow accumulation, likely resulting in increased concentrations of harmful contaminants and in a significantly changed seasonal salinity cycle in the estuary. The effects of these changes on estuarine ecosystems are uncertain but are likely to be adverse, further stressing an ecosystem which is already heavily impacted by a wide range of environmental problems.[60] Additionally, the significance of water diversions and the ongoing inability of water managers to fully address the needs for freshwater delivery to the Bay remains a major problem that is likely to be further exacerbated by future changes in precipitation patterns and timing.

Floods and Landslides

High precipitation events can cause both runoff problems, including flooding, and soil saturation leading to land-slides. Field et al. provide the following points on the combination of flooding and landslides:

Floods and Landslides[61]

Much of California is vulnerable to flooding, landslides, or both—and both become more likely when precipitation is high, storms are frequent, and above-normal precipitation continues for several years.

In low-elevation coastal watersheds, flooding is most common when a wet winter results in frequent storms.[62] In higher elevation watersheds, where surface water is stored as snow, flooding can result from unusually warm winter storms, a fast warming of the air, or springtime melting of the snow. In both kinds of habitats, landslides and slope failures are partly the result of precipitation and partly the result of land-use practices that allow or even encourage building in scenic but risky areas.

Numerous coastal mountain watersheds in northern California have rivers that flow over their banks once or twice every ten years. The Russian River exceeded flood stage (39 feet) six times between 1900 and 1950 and eight times between 1950 and 1990. In 1995 and 1997, Russian River floods created large economic losses, which were amplified by the presence of many housing developments within the 10-year flood plain. Similar flood events occur in southern California coastal watersheds during strong precipitation events.

Mountainous watersheds often generate floods during the spring melt season. The 1997 flooding in the Central Valley was triggered by a warm, late-winter storm. This storm's legacy included not only direct effects but also increased future risks because of the damage it caused to the existing levee system.

Levee break in the Sacramento-San Joaquin Delta.

Agriculture

California is the leading agricultural state in the U.S. by a considerable margin. The state has the most diverse crop mix of any region in the country, and probably the world. California is the only state to produce commercial quantities of a number of important crops including almonds, artichokes, clingstone peaches, figs, raisins, walnuts, pistachios, nectarines, olives, dates, and prunes. More than half the nation's fruits, nuts, and vegetables are grown in the state.[63] Climate change will impact these different crops in different ways. Unlike other regions of the country, California's assessment of potential impacts must undertake an analysis of different kinds of impacts, in different climate zones, to different crops and agricultural operations, in all seasons. This work is just beginning.

The over-all effect of climate change on crop yields has five major components:

1. variability (temperature, precipitation, and other factors such as wind and fog)
2. temperature (long-term changes)
3. elevated carbon dioxide
4. responses of plants to water
5. changes in pest dynamics (including rusts, molds, insects, etc.)

Other impacts may include water supply availability and cost, changes in market forces in California and globally, and impacts to infrastructure.

Potential impacts on animal operations, a major element of California agriculture, include high temperatures and the impacts of stronger precipitation events.

Some impacts may be beneficial, as the study on wine quality below indicates. Many others appear to hold difficult challenges for California farmers.

Diversity of Agricultural Production

Agricultural fields, orchards, and vineyards cover 11% of California's landscape.[64] Irrigated land area totals about 9 million acres, of which about 0.4 million acres are multiple cropped.[65] The following agricultural products lead the state's list of over 200 products:

California's Top 20 Agricultural Commodities, 1999

Rank	*Commodity*	*Value ($1,000)*
1	Milk and Cream	4,089,876
2	Grapes	2,737,805
3	Nursery	1,985,841
4	Cattle and Calves	1,223,123
5	Tomatoes	1,104,871
6	Lettuce	1,088,457
7	Strawberries	889,207
8	Flowers	775,175
9	Hay	693,326
10	Almonds	693,216
11	Cotton lint	673,669
12	Carrots	552,753
13	Chickens	515,084
14	Oranges	415,920
15	Broccoli	392,669
16	Avocados	327,002
17	Eggs/Chicken	263,690
18	Peaches	238,797
19	Rice	234,816
20	Cantaloupes	230,265

Source: California Department of Food and Agriculture, Resource Directory 2000.

Agriculture often involves long-term investments and long-term thinking. As Field et al. note with regard to perennial crops, decisions on crops are critically important.[66]

> In California, the abundance and economic importance of perennial crops, including fruits, nuts, and grapes, could have major implications for overall impacts of climate change on agriculture. First, it is not possible for growers of these crops to shift quickly to new cultivars as conditions change. A farmer needs a reasonable projection of future conditions throughout the productive life of the plants, which can be several decades for trees and vines. Second, the consequences of an extreme event can persist for many years. A severe drought or

a pest outbreak that kills a farmer's fruit trees, for example, eliminates production not just for the year of the drought or outbreak but for several successive years until a new crop of trees bear fruit.

Some Climate Impacts May Be Subtle

Not all climate impacts are obvious. For example, changes in precipitation patterns could bring rain at times when California is normally dry. While this may seem like a good thing for water supplies, it could in fact be devastating for many crops in the filed – from grapes to fruit and nut trees to row crops – due to various kinds of pest impacts. Rusts, moulds, fungus, and other pests may pose increasing challenges for farmers. The crop growth models used in the National Assessment did not include the effects of global warming on pests, diseases and weeds.

Fog is another interesting issue. The cool, moist conditions that fog provides at certain times and in certain areas is critically important to many valuable crops. If climate changes bring warmer, drier conditions and/or more wind, fog regimes may change. It is at this point unclear which direction the pattern may shift. Some coastal areas may get more fog, while inland valley fog may be subject to different influences. Modeling efforts to date have not provided much insight on this issue.

Another concern raised by farmers in California is the potential increase in night-time temperatures in the winter. Stone fruits (e.g. peaches, plums) require a certain number of "chill hours" to produce well. Warmer temperatures may reduce yields for some crops. On the other hand, warmer temperatures may mean fewer frost days, which would be good for some crops.

Timing of the seasons is also a concern for farmers. Spring may arrive earlier, and fall later. While this extended growing season may afford opportunities for some crops, California is already a year-round agricultural economy. Questions of timing and conditions for planting and harvest will face farmers. There may also be changes in the timing and relationship of predator-

prey relationship that will have important implications for farmers. If pests and predators have evolved to arrive at the same time, and conditions change, one or the other may arrive first. In either case, it would be expected that the predator-prey relationship will be disrupted. Either the prey populations may increase in the absence of the predator, or the predator arrives without prey. This may be an important issue for further research.

Carbon Dioxide Fertilization

The actual effect of carbon dioxide fertilization for crops in California is uncertain. As Field et al. note: [67]

> Most crop species respond positively to growth under doubled atmospheric carbon dioxide, with yield increases in the range of 10% to 50%.[68] Most of these growth increases, however, were measured on isolated plants in pots, and the actual enhancements might be smaller under field conditions.[69]

Temperature and carbon dioxide, along with moisture, interact in the plant growth process. Field et al. comment as follows:[70]

> Warming generally hinders crop yields, although the beneficial effects of elevated carbon dioxide in fertilizing plant growth may cancel out the effects of warming. If warming is accompanied by increased drought, however, the detrimental effects would be intensified. In California, 87% of the crop area is irrigated, and increased drought could be countered by human management. Yet there are severe constraints on increased irrigation. Growers of perennial crops, including fruits, nuts, and grapes, cannot shift quickly to new cultivars as conditions change; they are most vulnerable to shifts in climate and to extreme events such as drought or pest outbreaks. If California agriculture were to lose one or more

> crops to climate change, it would most likely be crops that use large amounts of water to produce crops of limited economic value. The economics of producing and selling crops will depend, in turn, on the impacts of global climate change on worldwide agricultural markets.

Agriculture and Potential Impacts on Water Systems

Agriculture, a sector particularly vulnerable to climate change, is also a major contributor to California's water pollution problems. Climate change could in fact worsen the problem. Substances found in agricultural waste water discharges include toxic metals and pesticides such as mercury, arsenic, lead, selenium, cadmium, Chlordane, PCBs, and many other dangerous compounds.[71] These substances pose significant threats to urban water supplies as well as fish and wildlife.

Lowell Lewis, William Rains, and Lynne Kennedy, noted a decade ago in *Global Climate Change and California Agriculture*, state that:

> Irrigation waters in some areas of the state are presently causing an accumulation of salts in qualities detrimental to crop yields and survival. Unless irrigation practices improve and leaching and proper drainage occur, many of these areas will loose their productive capacity in a matter of decades, with or without global warming.[72]

Excessive runoff is equally threatening to the state's agriculture. The reported damages from the El Niño storms in 1997-98 for agricultural losses was approaching $100 million in February. From dairy farmers losing cows to exhaustion as they try to escape the mud and are attacked by diseases,[73] to strawberry growers losing crops to the rain,[74] farmers have experienced significant losses due to strong variability. While field crops may be switched by the season, perennial crops including vineyards and orchards are long-term investments. Vineyards, a rapidly expanding area, are more susceptible to fungi when rains fall at the wrong time.

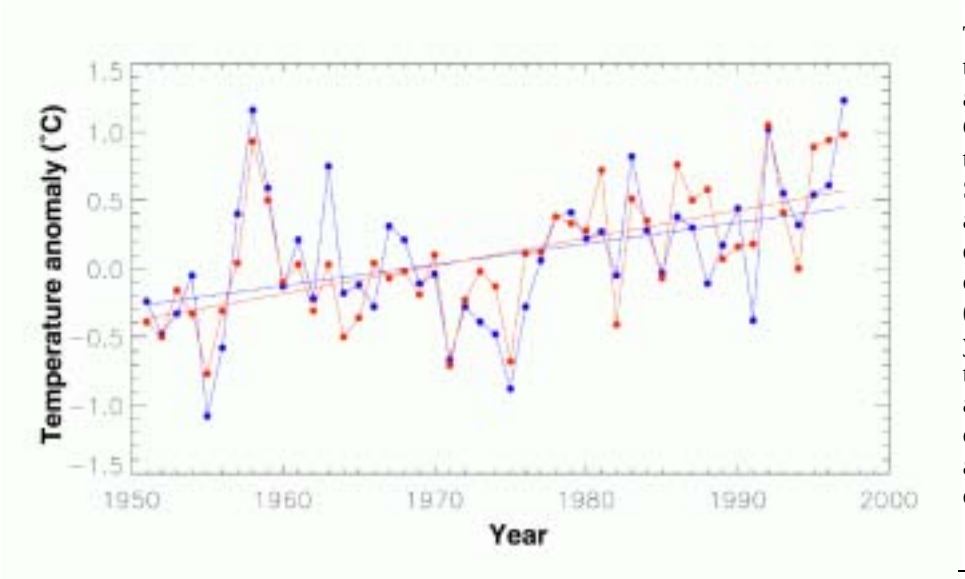
Potential Benefits of Climate Change for Agriculture

Not all impacts of climate change will be negative. As a team of researchers indicates in the case study presented below, some varieties of California wine may in fact benefit from climate change.

Asymmetric Climatic Warming Improves California Vintages[75]

Ramakrishna R. Nemani, Michael A. White, Daniel R. Cayan,
Gregory V. Jones, Steven W. Running and Joseph C. Coughlan

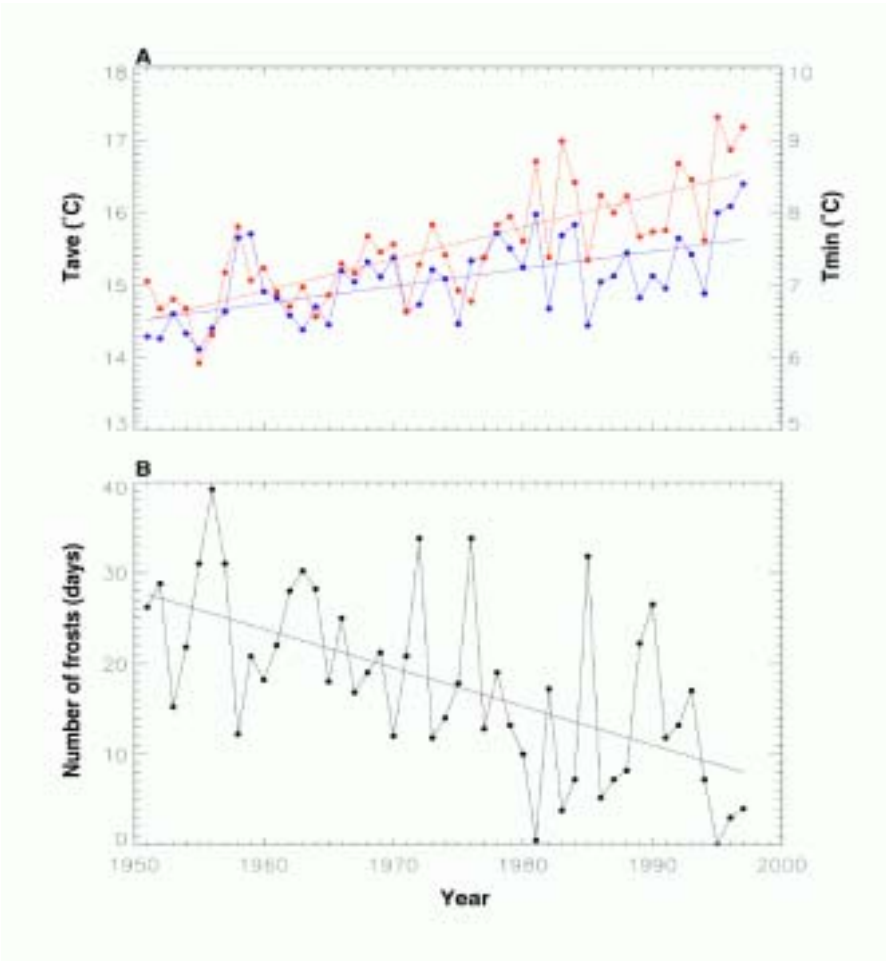
Air temperature warming along coastal California from 1951-1997 has benefited the premium wine industry, as catalogued in larger yields and higher quality from Napa/Sonoma valleys. Climatic changes were asymmetric, with greatest warming at night and during spring. Warming was associated with large increases in eastern Pacific sea surface temperatures (SSTs) and higher atmospheric water vapor. although the average temperature warming trend was modest (1.13 degrees C/47 years), there was a 20 day reduction in frost occurrence and a 65 day increase in frost free growing season length. Because regional scale SSTs persist for 6-12 months, predicting vintage quantity and quality from previous winter conditions appears possible.



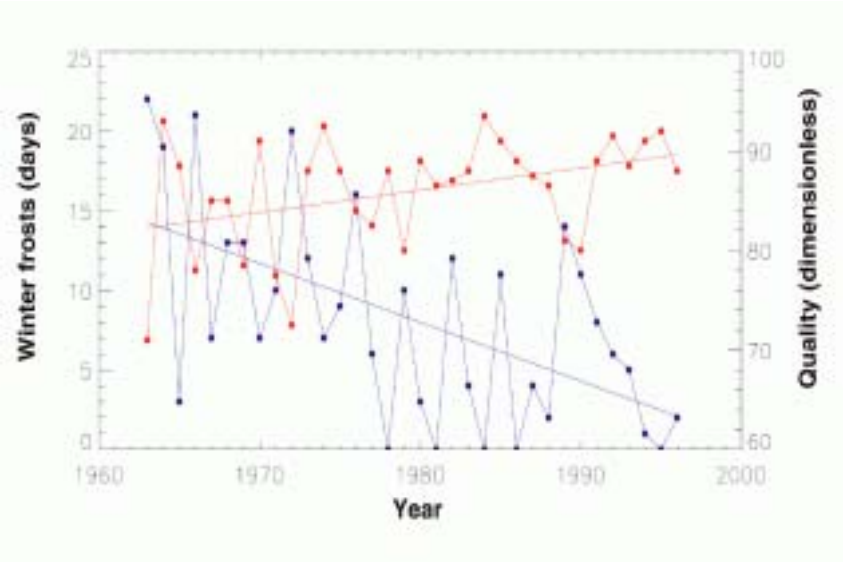
This figure above shows the standardized anomalies of coastal California average air temperatures and Pacific SSTs. SSTs (blue line and circles) are from a 5 degree by 5 degree grid centered at 35N 125W (0.71 degrees C over 47 years, p=0.0030); air temperatures (red line and circles) are north and central coast divisional averages (0.94 degrees C over 47 years, p<0.001).

The increased post 1976 warming trends are part of a well documented shift in Pacific climate (see C.C. Ebbesmeyer et al., in *Proceedings of the Seventh Annual Pacific Climate (PACLIM) Workshop*, J.L. Betancourt, V.L. Tharp, Eds. Interagency Ecological Studies Program Technical Report 26, California Department of Water Resources, Sacramento, CA, 1990, pages 115-126). The strong correlation (R=0.80) suggests that land and ocean warming is coupled through a water vapor feedback (see for example J.A. McGowan, D.R. Cayan and L.M. Dorman in *Science* volume 281 (1998) pages 210-217). Moist Pacific air resulting from warmer SSTs, combined with shifts in sea level pressures leading to increased southwesterly winds, increases coastal atmospheric humidity and dewpoint temperature. Higher dewpoint temperatures lead to higher minimum (night-time) temperatures through the latent heat of condensation. Finally, enhanced water vapor increases cloud cover, further increasing minimum temperatures through re-radiation of longwave energy.

Napa/Sonoma climatic changes. (A) The average temperature increased 1.13 degrees C over 47 years ($p<0.001$, blue line and circles) with nearly all warming caused by increases in minimum temperature (2.06 degrees C over 47 years, $p<0.001$, red line and circles). Consequently, the diurnal temperature range declined by 1.87 degrees C over 47 years ($p<0.001$). Contribution of the minimum temperature to the average temperature increase is higher than in global trends. (B) Napa/Sonoma frost decreased 71% over 47 years ($p<0.001$). If the current trend continues, Napa/Sonoma will become a frost-free climate, indicating a fundamental shift in ecosystem function.



This figure shows the observed relation between winter frost frequency and wine quality ratings. Buds damaged by frosts(blue line and circles) delay subsequent phenological events, leading to uneven maturity and poor wine quality, (red line and circles). Decoupling between quality and number of frosts during the 1980s is associated with an absence of severe frosts (minimum temperature less than -3 degrees C). In addition to improving crop quality by reducing frost damage, a low number of frosts generally forecasts a favorable year for Napa/Sonoma wine production, including warm springs and low growing season diurnal temperature range.



Forestry

Forestry has been an important economic activity in California since before gold was discovered (at a saw mill) in the Sierra Nevada. Timber extraction is declining, but the sector provides about $1 billion to the state's economy annually, much of it from public lands. Field et al. provide the following summary: [76]

> Commercial forestry is a substantial industry in California, with a 1996 harvest of 2.2 billion board feet that generated revenues of nearly $1 billion. Most of the harvest comes from national forests, which cover 20.5 million acres of California. Only 13% of the 1996 revenue came from forests on private land. The state's dominant timber species are mixed conifer (Ponderosa pine, sugar pine, Jeffrey pine, red fir, white fir), Douglas fir, and redwood. Redwood breaks the pattern of primarily federal ownership, with more than 85% of that forested area privately owned.

The potential impacts of climate change and variability on forest systems is related to moisture, temperature, pest population dynamics, and nutrients. Under certain conditions, carbon dioxide fertilization may enhance forest growth. Field et al. provide a good summary: [77]

> The responses of California forest species to climate change will depend critically on changes in drought and in the availability of mineral nutrients in the soil. If water and nutrients are sufficient, elevated carbon dioxide is likely to enhance forest production. The lack of studies on mature trees makes it difficult to predict increases in growth rates, but it would not be surprising to see growth increase under doubled carbon dioxide by approximately 25%.[78] Even if this level of stimulation persisted for only a few years after seedlings are established,[79] the cumulative nature of plant growth ensures that the stimulation could still have a dramatic effect, either on the time it takes the trees to reach harvestable size or in their ultimate size at maturity.
>
> In regions such as the Sierra Nevada, where neither water nor nutrients are severely limiting to plant growth, elevated carbon dioxide is likely to enhance forest production. In places where warming leads to increased drought or where soil nutrients are limiting, however, forest production may not be stimulated, and it could decline. As in other California ecosystems, changes in the pattern of fires, disease, or pest outbreaks have the potential to modify or conceivably even reverse the predicted responses of forests to elevated carbon dioxide and warming.
>
> In the Sierra Nevada, modeling experiments have predicted small increases in the total plant material produced per year.[80] In places where warming leads to increased drought or where mineral nutrients are limiting, however, forest production may not be stimulated, and it could decline.[81] Several model simulations indicate decreased net primary productivity in north-western California. In some parts of the world, the human-generated rain of nitrogen pollution could at least partially alleviate soil nutrient shortages.[82] Nitrogen deposition could be important in California, although current rates of deposition are too low to play a dominant role in nutrient budgets. In forests, as in other California ecosystems, fires, pests, and pathogens have the potential to greatly affect how ecosystems respond to climate change, conceivably even reversing the predicted responses to elevated carbon dioxide.

Forests are already impacted by air pollution, past forest practices, and other stresses. Given the critical role forests play as watersheds for the state's water supplies (affecting both quality and timing of runoff) and to economic sectors such as tourism, it is important that potential climate impacts be studied further.

Energy Supply Systems

Climate change will impact the generation, distribution, and use of energy. Increases in temperatures, changes in precipitation patterns and levels, and sea level rise will all have effects on energy infrastructure and systems.

The following chart shows California's electricity generation for 1991 through 2000. Note that hydropower production fluctuates year to year depending on runoff.

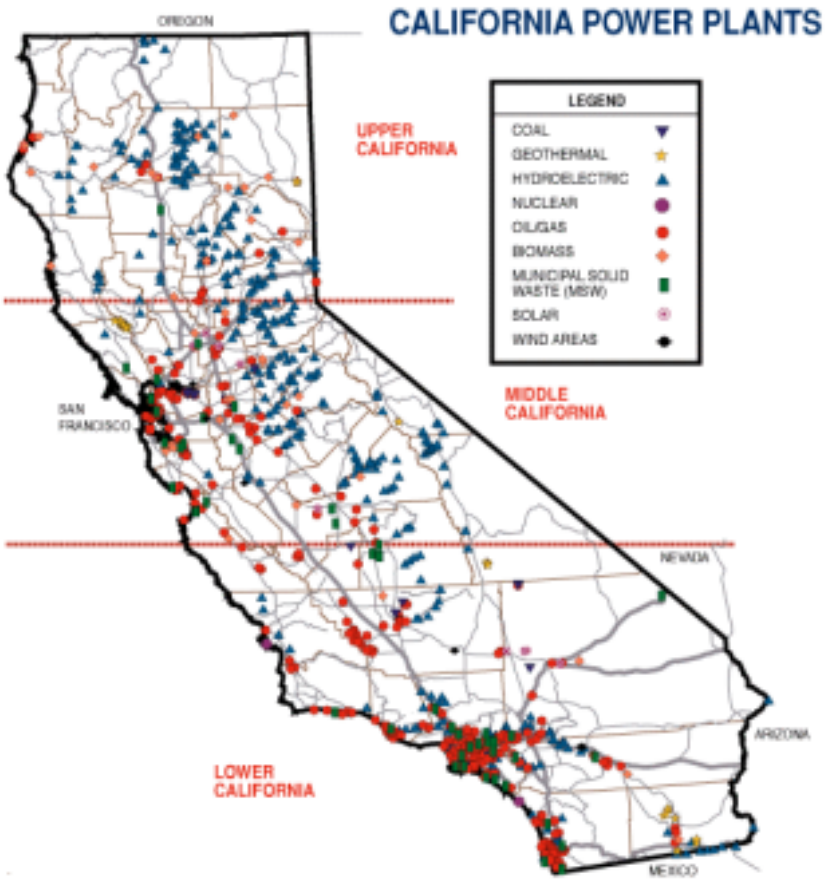
CALIFORNIA ELECTRICAL ENERGY GENERATION, 1991 TO 2000
TOTAL PRODUCTION, BY RESOURCE TYPE[83]
(Millions of kilowatt hours)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Total Generation:	**242,343**	**245,535**	**242,026**	**256,719**	**256,367**	**253,621**	**255,080**	**276,412**	**275,803**	**280,497**
Hydroelectric	23,244	22,373	41,595	25,626	51,665	47,883	41,400	48,757	41,627	42,053
Nuclear	37,167	38,622	36,579	38,828	36,186	39,753	37,267	41,715	40,419	43,533
Coal	23,442	32,435	22,907	25,095	17,925	25,460	27,114	34,537	36,327	36,804
Oil	523	107	2,085	1,954	489	693	143	123	55	449
Gas	75,828	87,032	70,715	95,025	78,378	66,711	74,341	82,052	84,703	106,878
Geothermal	15,566	16,491	15,770	15,573	14,267	13,539	11,950	12,554	13,251	13,456
Organic Waste	7,312	7,362	5,760	7,173	5,969	5,557	5,701	5,266	5,663	6,086
Wind	2,669	2,707	2,867	3,293	3,182	3,154	2,739	2,776	3,433	3,604
Solar	719	700	857	798	793	832	810	839	838	860
Other	0	2	0	0	0	343	896	230	0	0
Energy Imports	55,873	37,704	42,892	43,354	47,514	49,696	52,720	47,563	49,487	26,774

Source: California Energy Commission (see sources).

The following map indicates the location of power plants in California by generation type.[84]

Power Plants in California[85]



Source: California Energy Commission (see sources).

Transmission Systems

Electrical transmission systems in California are shown by utility area below. The links to the western grid system are also indicated. Climate impacts to the distribution system due to extreme events was identified as a key concern of utility company representatives at the California regional workshop.[86]

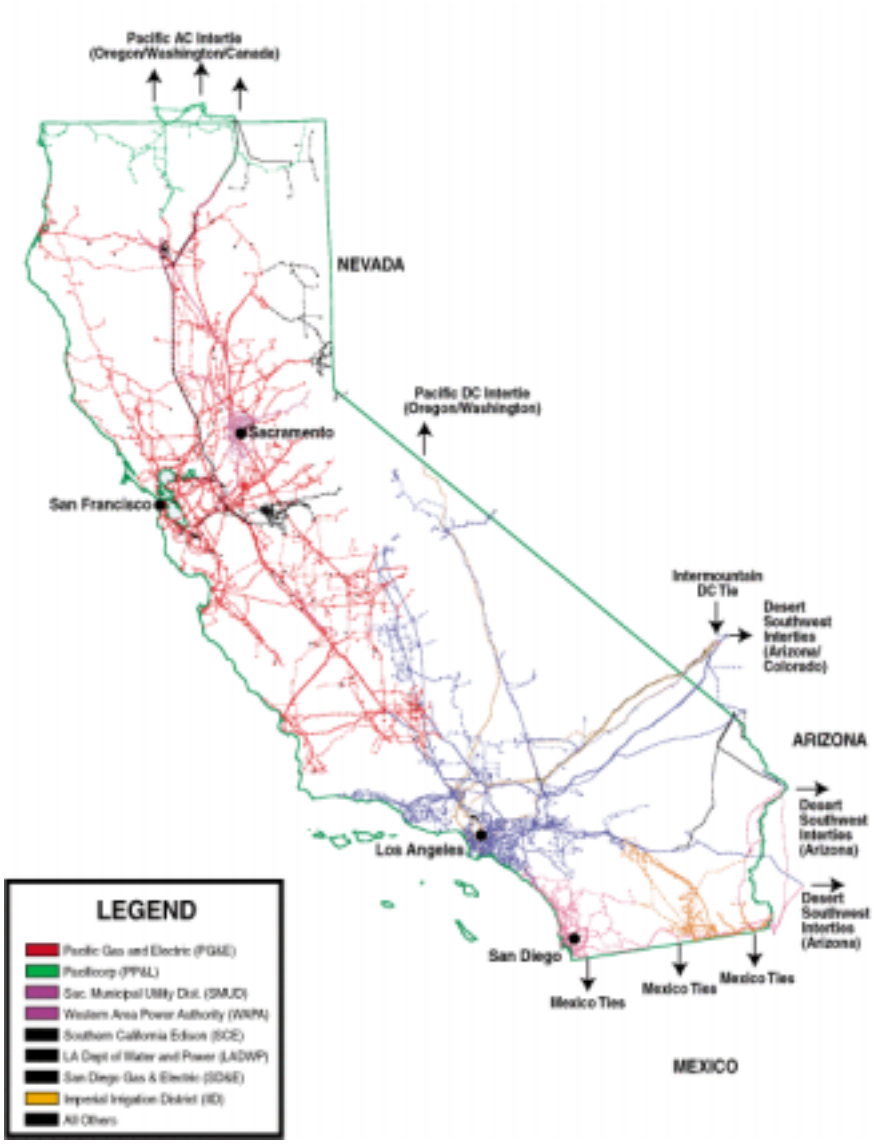
Increased temperatures may lead to a series of impacts on transmission systems. As the southwest assessment reports:[87]

> High temperatures also cause conductors to stretch and sag closer to the ground and higher system loading heats conductors through electrical resistance. With the combination of electrical and environmental heating, conductors can sag low enough to flash over to objects below, such as trees, causing fires and taking

transmission lines out of service. For this reason, transmission capacity is actually less when demand for electricity is greatest.

Transmission and distribution (both wires and pipelines) are vulnerable to climate change. An estimated $1 billion in damage was done to PG&E's system in 1989 from El Niño.[88]

California's Major Electric Transmission Lines[89]

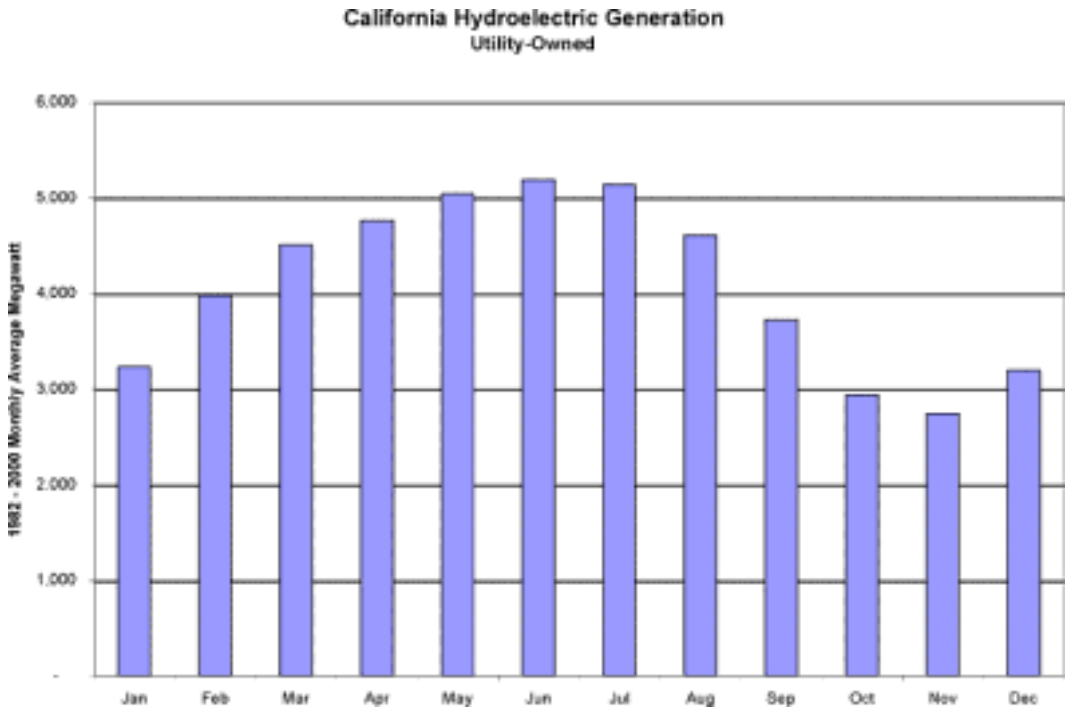


Source: California Energy Commission (see sources).

Hydropower

Hydropower generation in California will be affected by changes in precipitation levels and by pattern changes in how the precipitation arrives.[90] Less snowpack will mean lower levels of hydro generation in the summer and fall seasons due to reduced runoff in those seasons. If precipitation is at the same or greater levels as the models currently indicate, additional hydropower will be available during the winter and spring.

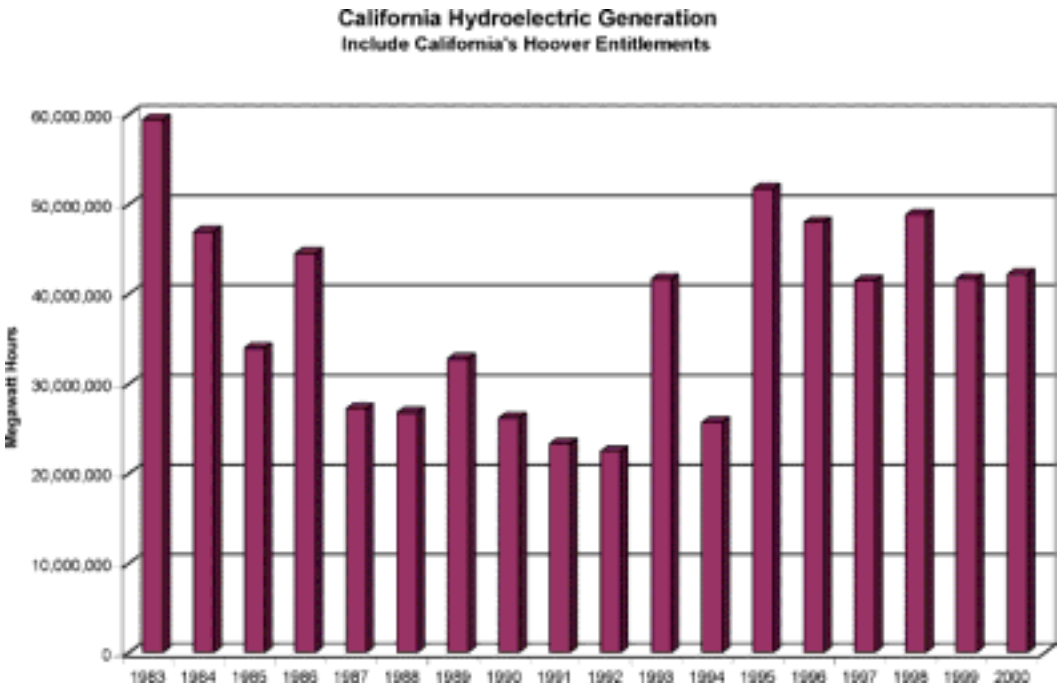
Monthly average hydropower production for 1982-2000 is plotted below:[91]



Source: California Energy Commission (see sources).

The ability of hydropower systems to capture this energy is limited, however, by the capacity of the systems. On balance, hydropower is more useful and valuable within the grid mix of generation sources when it is available throughout the summer and fall peak seasons.

The following graph shows California hydro production, including power from Hoover Dam:[92]



Source: California Energy Commission (see sources).

California produces significant amounts of hydropower. The USGS reports that in 1995, California produced 47,000 megawatt hours from hydroelectric facilities.[93] This level is second only to the Pacific Northwest in the United States. Climate change will potentially impact hydropower production. The National Water Sector report makes the following observations:[94]

> Variability in climate already causes variations in hydroelectric generation. During a recent multi-year drought in California, decreased hydropower generation led to increases in fossil-fuel combustion and higher costs to consumers. Between 1987 and 1991, these changes cost ratepayers more than $3 billion and increased greenhouse gas emissions.[95] Because of conflicts between flood-control functions and hydropower objectives, human-induced climate change in California may require more water to be released from California reservoirs in spring to avoid flooding. This would result in a reduction in hydropower generation and the economic value of that generation. At the same time, production of power by fossil fuels would have to increase to meet the same energy demands in California at a cost of hundreds of millions of dollars and an increase in emissions of greenhouse gases.[96]

Natural Gas Infrastructure

Natural gas provides the largest fraction of primary energy for electricity generation in California (see chart above). Most of California's supply of natural gas (approximately 85%) is imported from the Southwest, Canada, and the Rock Mountain Region. In 1999, the breakdown was as follows: In-State 16%, Southwest 46%, Canada 28%, Rockies 10%.[97]

The most likely impact of climate change and variability on the natural gas infrastructure is on the distribution system. Pipelines and related equipment are vulnerable in certain locations to land slides. Fire is also a potential threat.[98]

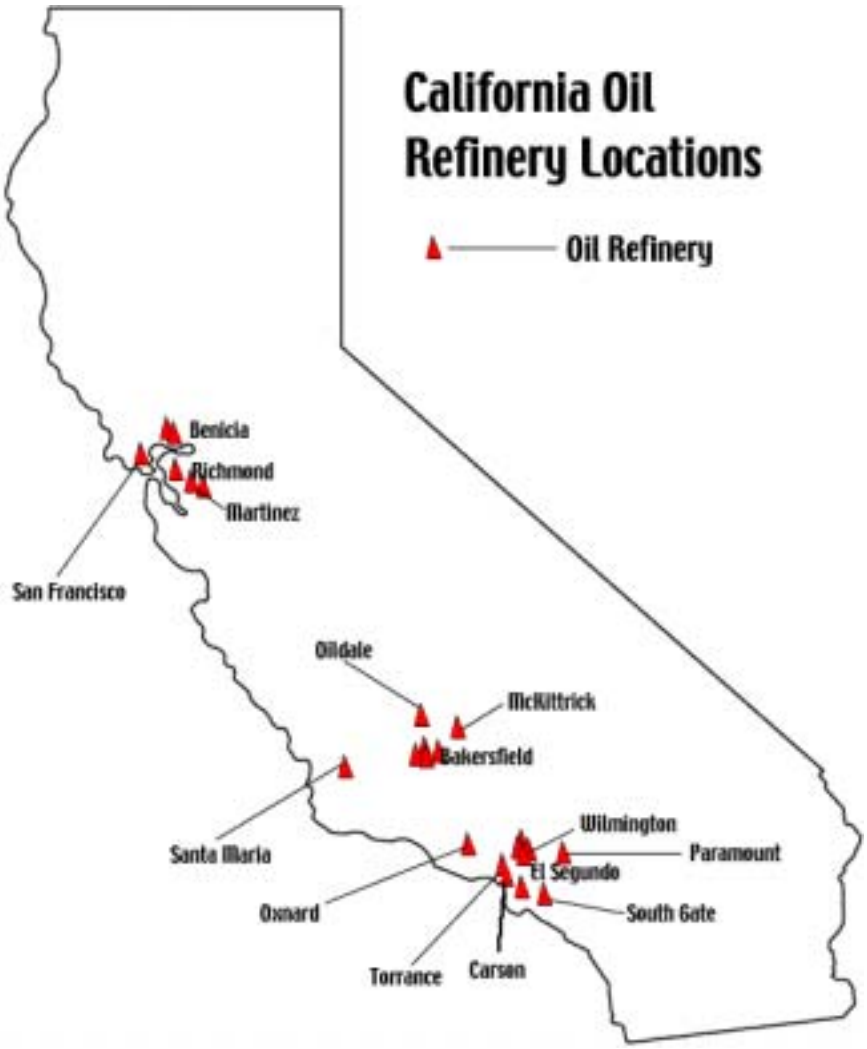
Major Natural Gas Pipelines in California[99]

Source: California Energy Commission (see sources).

Petroleum Production and Distribution

California produces almost half of its petroleum supplies. In 2000, the breakdown was as follows: In-State 49.5%, Alaska 24.8%, foreign 25.7%.[100] Oil is processed and refined is several areas of California as identified below. The potential impacts to petroleum extraction, transport, and refining include ocean and coastal impact to off-shore platforms and related support facilities along the coast, and coastal pipelines and processing facilities. Land slides, fire, and flooding could also impact pipelines, wells, and related extraction equipment.

Oil Refinery Locations in California[101]



Source: California Energy Commission (see sources).

Wind Energy

Potential impacts of climate change on wind regimes in California are uncertain and merit further research. Wind-generated power in California will be impacted by changes in timing and patterns. It is possible that increased temperatures in inland areas will increase wind flows through areas where existing wind farms are located (San Gorgonio Pass, Altamont Pass, and the Tehachapi Mountains). This is because temperature differential is the primary source of these winds.

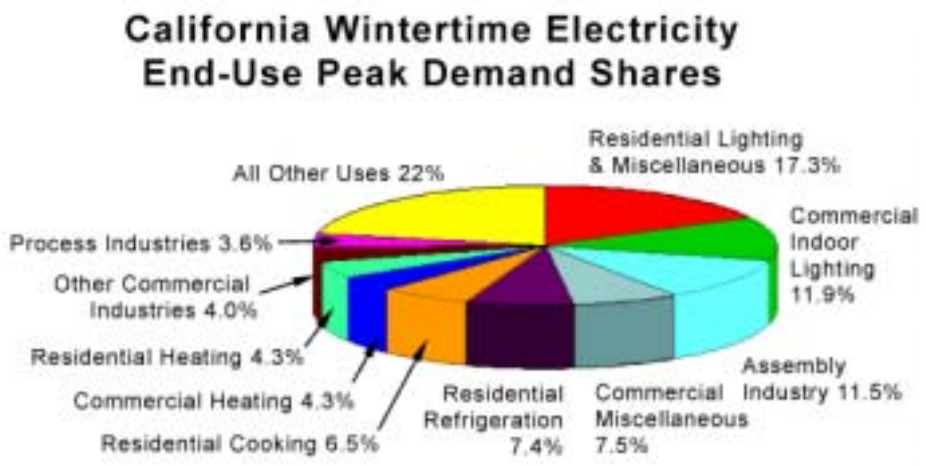
California Wind Resource Potential[102]

Source: California Energy Commission (see sources).

Energy Use

Climate change and variability will have impacts on energy use levels and patterns. California's peak power demand occurs in the afternoon during summer months due in large measure to air conditioning. Peak power use is important because systems must be designed to handle both the generation and transmission of power to meet the highest levels of demand. The black-outs and brown-outs that California experienced over the past several years were centered on peak uses.

Hotter conditions in the summer would increase the air conditioning demand and necessitate increased power generation as well as possible changes to the transmission and distribution systems. Warmer conditions in the winter, on the other hand, would reduce heating requirements. Heating is not a large factor in winter peak demand, however, as the following chart indicates.



Source: California Energy Commission, Electricity Office. 2001.[103]

Mining

Extractive industries may be impacted in various ways by climate change and variability. The Southwest Regional Assessment notes that extractive industries are directly vulnerable to climate variability in two main areas: water availability for operations, and avoiding impacts caused by too much water. [104]

> Water is an extremely important resource to many of the physical plants. Water is used in virtually all key processes associated with extractive industries in the Southwest. Process water is usually stored and reused, with some continual supplementation from the fresh water system. Process water may also be derived from collection of storm water not suitable for release to natural waterways. In

operations that are dependent on process water, such as leaching and milling facilities, climate variability can have a significant effect.

Most process water storage is in open tanks and natural or lined reservoirs. These facilities can experience significant losses to evaporation, or significant gains from rain events. Planning for probable needs and conditions dictates particular volumes of process water to be kept in storage. Either shortages, or influxes in excess of storage capacity, can lead to process interruptions and/or additional costs: normally, an extractive or processing facility remains in a delicate balance between storing too much or not enough water, and has limited ability to increase storage space available or secure additional water resources.

Another consideration is the ability to control excessive inflows of water directly into open pits of mines from precipitation, which can impede or shut down operations, resulting in lost revenues. Therefore, climate variability makes the industry more vulnerable through fluctuating water availability, precipitation patterns, and altered groundwater levels and stream flows.

The ability to control potential migration of contaminants into the environment—thereby complying with current and future environmental regulations that can involve significant fines—is a central regulatory and economic concern to the industry. Quality of water leaving facilities, especially mines, is an important concern for the industry because of the need for compliance with current local and federal clean water standards. A typical mining operation must collect and use or process all precipitation that falls within the limits of the facility, or that otherwise comes in contact with unnaturally exposed material, especially in the concentration and beneficiation steps in mining procedures. Infrastructure at a facility is developed to handle expected amounts of precipitation. In most cases, process equipment and systems established to handle the water represent significant capital investment (commonly millions of dollars per facility). Development of the infrastructure usually takes years. These financial and planning requirements mean that there is vulnerability to climate variability. If magnitude and frequency of storm events increase, systems in place may be insufficient to prevent successful containment of excess water, leading to pollution of streams and groundwater, regulatory violations, and fines or cessation orders for non-compliant operations.

Summary

California's economy is remarkably diverse. Potential impacts from climate change extend from the coastal sector to the deserts, and from the rich agricultural valleys to the alpine mountain areas.

Extreme weather events are of concern in a number of sectors. The recent experience of drought and then above normal precipitation and floods, along with heat waves and fire events, provides the state with a set of specific examples of the kinds of impacts climate can produce. This is not to argue that these events are directly related to climate change. Rather, the lesson is that if warming conditions bring more events like these, we have some idea of what to plan for.

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Part 4. Potential Impacts of Climate Change and Variability on Human Health

Human health in the California region is likely to be impacted by climate change and variability. Several recent studies have addressed potential implications for human health at the national and international levels.[1] The U.S. National Assessment notes that "Some of these outcomes are relatively direct (e.g., the effects of exposure to extreme heat or extreme events); others involve intermediate and multiple pathways, making assessments more challenging."[2] This section draws in particular on the sectoral analysis on health of the U.S. National Assessment, *The Potential Health Impacts of Climate Variability and Change for the United States*;[3] a useful summary by Balbus and Wilson, *Human Health and Global Climate Change: A Review of Potential Impacts in the United States*, written for the Pew Center on Climate Change;[4] and the Southwest Regional Analysis for the U.S. National Assessment, *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change*.[5] There have been no comprehensive studies of the potential implications of climate change for human health in California.

Balbus and Wilson provide an important point regarding certainty and health issues:

> It is critical to keep in mind that *uncertainty* regarding adverse health outcomes *is not the same as the certainty of no adverse outcomes*. Given the potential scope and irreversibility of ecosystem changes and consequent effects on human health and society, traditional public health values would urge prudent action to prevent such changes. The possibility of relatively sudden but unpredictable consequences further raises the value of climate change mitigation for health concerns.[6]

While the U.S. Assessment concluded that "definitive statements" on future health outcomes is not possible as this time,[7] the study identifies a number of areas of concern outlined below.

Key Findings Regarding Potential Health Impacts

An analysis of possible health impacts resulting from climate change and variability was conducted for the U.S. National Assessment by a distinguished team of experts from academia, government, and the private sector. The team examined the potential impacts of climate variability and change on human health. They note that: "If climate change occurs as projected, it may have significant impacts on *virtually all systems* on which human life depends – biologic, hydrologic, and ecologic."[8]

The health sector team identified five categories of health outcomes that are most likely to be affected by climate change: [9]

1. weather and/or climate variables
2. temperature-related morbidity and mortality
3. health effects of extreme weather events
4. air-pollution-related health effects; water- and food-borne diseases
5. vector- and rodent-borne diseases.

This section opens with a review of the key findings of the national assessment. It then presents information on several specific health concerns identified in studies including the Southwest Assessment.

Potential Impacts of Projected Climate Change on Health[10]

Temperature-related illnesses and deaths.

Heat and heat waves are projected to increase in severity and frequency with increasing global mean temperatures. Studies of heat waves in urban areas have shown an association between increases in mortality and increases in heat, measured by maximum or minimum temperature, heat index (a measure of temperature and humidity), or air-mass conditions.[11] For example, after a 5-day heat wave in 1995 in which maximum temperatures in Chicago ranged from 93 to 104°F, the number of deaths increased 85% over the number recorded during the same period of the preceding year.[12] At least 700 excess deaths (deaths beyond those expected for that period in that population) were recorded, most of which were directly attributed to heat.[13]

Exposure to extreme and prolonged heat is associated with heat cramps, heat syncope (fainting), heat exhaustion, and heat stroke. These health effects appear to be related to environmental temperatures above those to which the population is accustomed. Although long-term physiologic adaptation to heat events has not been documented, adaptation appears to occur as the summer season progresses; heat waves early in the summer often result in more deaths than subsequent heat waves or than those occurring later in the summer.[14] Heat waves are episodic, and although populations may adapt to gradual temperature increases, physiologic adaptation for extreme heat events is unlikely.

The heat index and heat-related mortality rates are higher in the urban core than in surrounding areas.[15] Urban areas retain heat throughout the nighttime more efficiently than do outlying suburban and rural areas.[16] The absence of nighttime relief from heat for urban inhabitants may be a factor in excessive heat-related deaths. The size of U.S. cities and the proportion of U.S. residents living in them is projected to increase; therefore, the population at risk for heat-related illnesses and death may also increase.

Health effects related to storms, tornadoes, hurricanes, and precipitation extremes.

Climate change may alter the frequency, timing, intensity, and duration of extreme weather events,[17] i.e., meteorologic events that have a significant impact on local communities. Injury and death are the direct health impacts most often associated with natural disasters. Secondary health effects may also occur. These impacts are mediated by changes in ecologic systems and public health infrastructures, such as bacterial proliferation and the availability of safe drinking water. The health impacts of extreme weather events such as floods and storms hinge on

the vulnerabilities of the natural environment and the local population, as well as on their capacity to recover. A community's level of preparedness greatly affects the severity of the health impacts of an extreme event.

From 1945 to 1989, 145 natural disasters caused 14,536 deaths in the United States, an average of 323 deaths/year.[18] According to the National Weather Service,[19] severe storms caused 600 deaths and 3,799 reported injuries in 1997. Floods are the most frequent natural disaster and the leading cause of death from natural disasters in the United States; the average annual loss of life is estimated to be as high as 146 deaths/year.[20]

Air-pollution-related health effects.

Air pollutants have many sources: natural (e.g., vegetation and volcanoes), agricultural (e.g., methane and pesticides), commercial (e.g., dry cleaning operations and auto body shops), industrial (electric power plants and manufacturing facilities), transportation (truck and automobile emissions), and residential (home gas, oil burners, and wood stoves). Ambient levels of regulated air pollutants (which include particulate matter, ozone, carbon monoxide, and sulfur and nitrogen oxides) have generally dropped since the mid-1970s, but air quality in many parts of the country falls short of health-based air quality standards.

Air pollution is related to weather both directly and indirectly. Climate change may affect exposures to air pollutants by *a*) affecting weather and thereby local and regional pollution concentrations;[21] *b*) affecting anthropogenic emissions, including adaptive responses involving increased fuel combustion for power generation; *c*) affecting natural sources of air pollutant emissions;[22] and *d*) changing the distribution and types of airborne allergens.[23] Local weather patterns, including temperature, precipitation, clouds, atmospheric water vapor, wind speed, and wind direction influence atmospheric chemical reactions. They can also affect atmospheric transport processes and the rate of pollutant exports from urban and regional environments into the global scale environments.[24] In addition, the chemical composition of the atmosphere may in turn have a feedback effect on the local climate.

If the climate becomes warmer and more variable, air quality is likely to be affected. For example, if warmer temperatures lead to more air-conditioning use, power plant emissions could increase without additional air pollution controls. Increased temperatures may enhance the formation of ground-level ozone, particularly in urban areas.[25] Changing weather patterns contribute to yearly differences in ozone concentrations.[26]

Exposures to air pollutants have serious public health consequences. Ground-level ozone can exacerbate respiratory diseases by damaging lung tissue, reducing lung function, and sensitizing the lungs to other irritants.[27] Short-term drops in lung function caused by ozone are often accompanied by chest pain, coughing, and pulmonary congestion.[28] Epidemiologic studies have found that exposure to particulate matter can aggravate existing respiratory and cardiovascular diseases, alter the body's defense systems against foreign materials, damage lung tissue, and may cause cancer and premature death.[29] Health effects of exposures to carbon monoxide, sulfur dioxide, and nitrogen dioxide can include visual impairment, reduced work capacity, aggravation of existing cardiovascular diseases, effects on breathing, respiratory illnesses, lung irritation, and alterations in the lung's defense systems.[30]

In addition to affecting exposure to air pollutants (whether man-made or naturally emitted), climate change may also play a role in human exposure to airborne allergens. Plant species are sensitive to weather, and warmer temperatures may enhance pollen production or alter the geographic distribution of plant species.[31] Consequently, climate change may adversely impact the occurrence and severity of asthma, the most common chronic disease of childhood, and affect the timing or duration of seasonal allergies such as hay fever.

Water- and Food-borne diseases.

More than 200 million people in the United States have direct access to treated public water supply systems, yet as many as 9 million annual cases of waterborne disease have been estimated,[32] although high uncertainty accompanies this estimate, and reporting is variable by state.[33] Although most of these cases of waterborne disease involve mild gastrointestinal illnesses, other severe outcomes such as myocarditis are now recognized. These infections and illnesses can be chronic and even fatal in infants, the elderly, pregnant women, and people with weakened immune systems.[34]

In the United States, food-borne diseases are estimated to cause 76 million cases of illness, with 325,000 hospitalizations and 5,000 deaths/year.[35] Microbiologic agents in water (e.g., viruses, bacteria, and protozoa) can contaminate food (e.g., shellfish and fish). In addition, there have been instances of contamination of fresh fruits and vegetables by waterborne pathogens.[36]

The routes of exposure to water- and food-borne diseases include ingestion, inhalation, and dermal absorption of microbial organisms or algal toxins. For example, people can ingest waterborne microbiologic agents by drinking contaminated water, by eating seafood from contaminated waters, or by eating fresh produce irrigated or processed with contaminated water.[37] They also may be exposed by contact with contaminated water through commerce (e.g., fishing) or recreation (e.g., swimming).[38] The waterborne pathogens of current concern include viruses, bacteria, and protozoa. Examples include *Vibrio vulnificus*, a naturally occurring estuarine bacterium responsible for a high percentage of the deaths associated with shellfish consumption;[39] *Cryp-tosporidium parvum* and *Giardia lamblia*, associated with gastrointestinal illnesses;[40] and biologic toxins associated with harmful algal blooms.[41] Many of these were discovered only recently and are the subject of ongoing research.

Changes in precipitation, temperature, humidity, salinity, and wind have a measurable effect on the quality of water used for drinking, recreational, and commercial use, and as a source of fish and shellfish. Direct weather associations have been documented for waterborne disease agents such as *Vibrio* bacteria,[42] viruses,[43] and harmful algal blooms.[44]

For many waterborne diseases, the management and disposal of sewage, biosolids, and other animal wastes and the protection of watersheds and fresh water flows are critical variables that impact water quality and the risk of waterborne disease.[45]

Vector- and rodentborne diseases.

Diseases transmitted between humans by blood-feeding arthropods (insects, ticks, and mites), such as plague, typhus, malaria, yellow fever, and dengue fever were once common in the United States and in Europe.[46] The ecology and transmission dynamics of these vector-borne infections are complex and the factors that influence transmission are unique to each disease. It is not possible, therefore, to make broad generalizations on the effect of climate on vector-borne diseases.[47] Many of these diseases are no longer present in the United States, mainly because of changes in land use, agricultural methods, residential patterns, human behavior, and vector control. However, diseases that may be transmitted to humans from wild animals (zoonoses) continue to circulate in nature in many parts of the country. Humans may become infected with the pathogens that cause these diseases through transmission by insects or ticks. For example, Lyme disease, which is tick-borne, circulates among white-footed mice in woodland areas of the Mid-Atlantic, Northeast, upper Midwest, and West Coast of the United States, and humans acquire the pathogen when they are bitten by infected ticks.[48] Fleaborne plague incidence increased in conjunction with increasing rodent populations after unseasonal winter-spring precipitation in New Mexico.[49]

Humans may also become infected with pathogens that cause zoonotic diseases by direct contact with the host animals or their body fluids, as occurs with Hantavirus Pulmonary Syndrome (HPS). Hantaviruses are carried by numerous rodent species and are transmitted to humans through contact with rodent urine, droppings, and saliva, or by inhaling aerosols of these products.

Most vector-borne diseases exhibit a distinct seasonal pattern which clearly suggests that they are weather sensitive. Rainfall, temperature, and other weather variables affect in many ways both the vectors and the pathogens they transmit. Rainfall may increase the abundance of some mosquitoes by increasing the number of their breeding sites,[50] but excessive rainfall can flush these habitats and thus destroy the mosquitoes in their aquatic larval stages. Increased humidity can extend vector survival times.[51] Dry conditions may eliminate the smaller breeding sites, such as ponds and puddles, but create productive new habitats as river flow is diminished. Thus, epidemics of malaria are associated with rainy periods in some parts of the world but with drought in others. High temperatures can increase the rate at which mosquitoes develop into adults, the rate of development of the pathogens in the mosquitoes,[52] and feeding and egg-laying frequency. The key factor in transmission is the survival rate of the vector.[53] Higher

temperatures may increase or reduce survival rate, depending on the vector, its behavior, ecology, and many other factors. Thus, the probability of transmission may or may not be increased by higher temperatures.

In the western United States, one study[54] predicted that a 3-5°C increase in average temperature may cause a northern shift in the distribution of both Western equine encephalitis (WEE) and SLE outbreaks and a decreased range of WEE in southern California based on temperature sensitivity of both virus and mosquito carrier.

Many other factors are important in transmission dynamics. For example, dengue fever--a viral disease mainly transmitted by *Aedes aegypti*, a mosquito that is closely associated with human habitation--is greatly influenced by house structure, human behavior, and general socioeconomic conditions. There is a marked difference in the incidence of the disease above and below the United States-Mexico border: in the period 1980-1996, 43 cases were recorded in Texas as compared to 50,333 in the three contiguous border states in Mexico.[55]

The tremendous growth in international travel increases the risk of importation of vector-borne diseases, some of which can be transmitted locally under suitable circumstances at the right time of the year.[56] Key preventive measures must be directed both at protecting the increasing number of U.S. travelers going to disease-endemic areas, as well as preventing importation of disease by U.S. and non-U.S. citizens. The recent importation of West Nile virus encephalitis into New York illustrates the continued need for vigilance for zoonotic diseases potentially brought in by imported animals or international travelers.[57] An active survey in Florida[58] recently documented under-reporting for some diseases, such as dengue fever, further demonstrating the need for improved surveillance to better estimate risk.

Potential Direct and Indirect Impacts on Human Health

Greater climate variability and changes in climate patterns would potentially cause both direct and indirect effects. Direct health impacts due to climate change include extreme events, such as storms resulting in flooding and landslides, heat waves and droughts resulting prolonged high temperatures and increased fire frequency and intensity. Secondary or indirect effects include damages to infrastructure causing, for example, sanitation and water treatment problems leading to an increase in water-borne infections. Air quality impacts such as increases in tropospheric, (i.e., ground-level) ozone due to higher temperatures may also cause secondary health impacts.

Balbus and Wilson note that: “Direct effects involve mostly physical impacts that act to cause physiologic stress (e.g., temperature) or bodily injury (e.g., storms, floods, and fire). Direct effects tend to be observed soon after the causative weather event and are generally more easily modeled and understood than indirect effects. On the other hand, indirect effects, such as climate impacts on food supplies and the outbreak of vector-borne diseases, may operate through diverse pathways involving multiple variables. These more complex mechanisms may demonstrate a threshold or nonlinear response to increasing levels of a climate factor.”

Temperature

The US EPA comments on temperature impacts in the Los Angeles area specifically:[59]

> Higher temperatures and increased frequency of heat waves may increase the number of heat-related deaths and the incidence of heat-related illnesses. Cities

such as Los Angeles that experience occasional very hot, dry weather may be especially susceptible. One study estimates that a 3°F warming could almost double heat-related deaths in Los Angeles, from about 70 today to 125 (although increased air conditioning use may not have been fully accounted for). Little change in winter mortality is expected in Los Angeles. The elderly, particularly those living alone, are at greatest risk.

Heat waves are a particular concern. Balbus and Wilson note that: "Mortality from heat waves has been predicted to increase under most scenarios of climate change. The degree to which heat-related mortality rates increase will be determined by the ability to implement early warning systems and other interventions that focus on at-risk populations, as well as by the frequency of extreme heat waves and the changes in daytime temperature variation under future climate regimes." [60]

Heat Waves[61]

National Oceanic and Atmospheric Administration

Heat kills by taxing the human body beyond its abilities. In a normal year, about 175 Americans succumb to the demands of summer heat. Among the large continental family of natural hazards, only the cold of winter – not lightning, hurricanes, tornadoes, floods, or earthquakes-takes a greater toll. In the 40-year period from 1936 through 1975, nearly 20,000 people were killed in the United States by the effects of heat and solar radiation. In the disastrous heat wave of 1980, more than 1,250 people died.

And these are the direct casualties. No one can know how many more deaths are advanced by heat wave weather-how many diseased or aging hearts surrender that under better conditions would have continued functioning.

North American summers are hot; most summers see heat waves in one section or another of the United States. East of the Rockies, they tend to combine both high temperature and high humidity although some of the worst have been catastrophically dry.

Heat Index	**Possible heat disorders for Index people in higher risk groups**
130° or higher	heatstroke/sunstroke highly likely with continued exposure,
105°- 130°	sunstroke, heat cramps or heat exhaustion likely, and heatstroke possible with prolonged exposure and/or physical activity.
90°- 105°	sunstroke, heat cramps and heat exhaustion possible with prolonged exposure and/or physical activity.
80° - 90°	fatigue possible with prolonged exposure and/or physical activity

How Heat Affects the Body

Human bodies dissipate heat by varying the rate and depth of blood circulation, by losing water through the skin and sweat glands, and-as the last extremity is reached-by panting, when blood is heated above 98.6 degrees. The heart begins to pump more blood, blood vessels dilate to accommodate the increased flow, and the bundles of tiny capillaries threading through the upper layers of skin are put into operation. The body's blood is circulated closer to the skin's surface, and excess heat drains off into the cooler atmosphere. At the same time, water diffuses through the skin as perspiration. The skin handles about 90 percent of the body's heat dissipating function.

Sweating, by itself, does nothing to cool the body, unless the water is removed by evaporation-and high relative humidity retards evaporation. The evaporation process itself works this way: the heat energy required to evaporate the sweat is extracted from the body, thereby cooling it. Under conditions of high temperature (above 90 degrees) and high relative humidity, the body is doing everything it can to maintain 98.6 degrees inside. The heart is pumping a torrent of blood through dilated circulatory vessels; the sweat glands are pouring liquid-including essential dissolved chemicals, like sodium and chloride-onto the surface of the skin.

Too Much Heat

Heat disorders generally have to do with a reduction or collapse of the body's ability to shed heat by circulatory changes and sweating, or a chemical (salt) imbalance caused by too much sweating. When heat gain exceeds the level the body can remove, or when the body cannot compensate for fluids and salt lost through perspiration, the temperature of the body's inner core begins to rise and heat-related illness may develop. Ranging in severity, heat disorders share one common feature: the individual has overexposed or over-exercised for his age and physical condition in the existing thermal environment.

Sunburn, with its ultraviolet radiation burns, can significantly retard the skin's ability to shed excess heat. Studies indicate that, other things being equal, the severity of heat disorders tend to increase with age-heat cramps in a 17-year-old may be heat exhaustion in someone 40, and heat stroke in a person over 60. Acclimatization has to do with adjusting sweat-salt concentrations, among other things. The idea is to lose enough water to regulate body temperature, with the least possible chemical disturbance.

Temperature rise itself is likely to increase the incidence of heat-related stress and mortality. Highly susceptible people include the elderly and those with heart and respiratory problems, but anyone can be affected. The CDC reported an average of 175 deaths annually in the United States from weather-related heat stress between the years 1979 and 1995.[62] Specific risk is linked to a lack of air conditioning and isolation. "The lethality of a heat wave is enhanced by its occurrence early in the summer (before populations have had a chance to acclimate), by long duration, and by higher nighttime minimum temperatures."[63] The summer of 1995 provided an extreme example of a lethal heat wave in the mid-west, when more than 700 people died in Chicago.[64]

Bloomfield et al. note that certain communities may me disproportionately impacted:

> Low-income groups and communities of color have additional vulnerability to global warming. Members of these populations who live in urban areas are less likely to be able to leave the urban area during hot periods, are less likely to have air conditioning and as a result, spend more time exposed to high heat and smog. These populations are also less likely to receive adequate medical care, and are

more likely to have pre-existing respiratory illnesses, such as asthma, making them more vulnerable to additional smog and high temperatures.[65]

Indirect impacts of increased temperature include increased bacterial growth, which poses a threat of infection and contamination of food. "Higher ambient temperatures are likely to increase risk of bacterial growth sufficient to cause human infection. The growth of a highly centralized food processing and distributing industry over the past two decades in the United States has increased the importance of factors that can lead to the contamination of foodstuffs."[66]

Air Quality Impacts

Adverse health impacts caused by air pollutants are well documented in the literature.[67] California's South Coast Air Quality Management District provides a summary of health effects studies.[68] Specific air quality concerns in the context of climate change are: levels of particulates, tropospheric ozone, nitrogen oxides (NO_x), and sulfur oxides (SO_x).[69] Air quality is related to temperature, especially in cities. Ozone production increases with heat, exacerbating ozone-related health problems and environmental impacts. Prolonged exposure to ozone causes reduced lung function and aggravates asthma and other respiratory conditions. The potential impact of climate change on tropospheric ozone is of particular concern for human health.[70] Ozone exposure is a significant health issue, and ozone is the criteria air pollutant "to which the highest numbers of U.S. residents are currently exposed at levels above EPA standards."[71]

A study by Kinney and Ozkaynak of urban air pollution in Los Angeles County "found a significant association between daily mortality and ozone levels."[72] California's population, postwar industrial boom, agricultural success, and dependence on the automobile have resulted in troubling problems with air and water pollution. Cars and trucks are California's primary sources for air pollution, emitting ozone, carbon dioxide, carbon monoxide, nitrogen oxides, particulate matter, and other harmful substances.

In the Los Angeles area, population density, cars, climate, and geography conspire to create some of the nation's worst air quality. Other California cities including Bakersfield and Fresno are also struggling with severe air quality problems as the San Joaquin Valley suffers from air pollution from various sources. Pollutants from this region have caused Sequoia National Park to have the worst smog of any national park – and more days of unhealthy ozone than Los Angeles and New York City combined.[73]

In the South Coast Air Basin (including Los Angeles, Orange, and parts of Riverside and San Bernardino Counties), federal 1-hour ozone standards were exceeded on 60 days in 1998; nevertheless, this is a dramatic improvement over the 167 days of violation in 1980. [74] Ozone is largely a product of the transportation sector. Ozone (O_3) in the lower atmosphere is produced when sunlight initiates a photochemical reaction between oxides of nitrogen (NO_x) and hydrocarbons, both products of fossil fuel combustion. Exposure to ozone for several hours can create respiratory distress in as many as 20 percent of healthy adults and children, while prolonged chronic exposure can cause irreparable lung damage.[75] Ozone also causes tissue

damage to plants, decreasing productivity in agricultural crops, landscaping, and natural vegetation.

California's stringent auto emission control regulations and reformulated gasolines have made today's automobiles and trucks as much as 95 percent cleaner than cars running 30 years ago. However, the state has some 26 million vehicles on the roads, all emitting some pollutants. The increasing popularity of trucks and sport utility vehicles is also contributing to the state's problems – these vehicles produce 1.5 to 2.5 times the emissions of passenger cars. Increasing public pressure is prompting automakers to commit to reduce emissions by producing more electric hybrid cars and fuel-cell vehicles, as well as improving fuel efficiency in trucks and sport-utility vehicles.

Another significant air pollutant is particulate matter less than 10 microns in diameter, known as PM10. Health problems can result from prolonged exposure to PM10, particularly the particles less than 2.5 microns which can easily penetrate deep into the lungs. Ash, soot, and dust are the primary constituents of particulate matter pollution, but any solid or liquid particle smaller than 10 microns can contribute to this type of pollution. A major source of particulate matter is incomplete combustion of organic substances—from gasoline to wood. Various industrial activities—processing metal, wood, fiber, and many other materials—can also produce aerosols. In farming regions, agriculture contributes to particulate matter. Heavy equipment disking the soil and aerial application of pesticides and fertilizers can send huge amounts of dust and droplets into the air. An additional health concern from agricultural dust is the potential for soil pathogens to become airborne, such as that which causes Valley Fever.

Vector-Borne Diseases

Vectors are mechanisms or means by which diseases are transmitted. Insects often provide that mechanism, and the presence of insects is influenced by climate. Balbus and Wilson note that: "The principal vector-borne diseases currently afflicting people living in the United States are transmitted either by mosquitoes (e.g., St. Louis encephalitis, equine encephalitis, and La Crosse encephalitis – all viral diseases associated with inflammation of the brain), ticks (e.g., Lyme disease, Rocky Mountain spotted fever, ehrlichiosis – a bacterial disease characterized by fever and fatigue), or fleas (plague)."[76]

Vector-Borne Diseases[77]

Because insects and other invertebrates are cold-blooded and heavily dependent on the environment, climate plays a major role in their behavior, development, and reproduction. In addition, pathogen development is regulated by temperature. Thus, human diseases that are spread by these invertebrates may also be more affected by climate change than some other diseases. Vector-borne diseases result from transmission of infectious agents by arthropod vectors as they feed on human blood. Some vector- borne diseases such as malaria and dengue fever, termed anthroponoses, may be uniquely human infections in which an arthropod is able to transmit the microbe to another human only after first acquiring it from a human. Alternatively, many other vector-borne diseases of humans, termed zoonoses, involve infectious agents that normally are found primarily in animals, with occasional and

accidental transmission to people. The animals act as reservoirs for the disease, serving as hosts for the reproduction of disease agents in between human outbreaks. Should climate change improve longevity, increase reproduction, enhance biting, or increase the ranges of these vectors, an increase in the number of people infected could result. Likewise, similar effects on the vertebrate animals that serve as reservoirs for agents associated with hantaviral diseases (infectious viral pulmonary diseases), leptospirosis (a bacteria disease characterized by jaundice and fever), rabies, or vector-borne diseases could also result in greater human risk.

Several specific vector-borne diseases that may be influenced by climate change are of concern in California. Valley Fever and Hantavirus are discussed in detail here.

Climate Change and Valley Fever

Valley fever, or Coccidioidomycosis, is a serious health concern in California and the Southwest United States. The Regional Assessment for the Southwest, which overlaps its analysis with California, contains a valuable review by Andrew C. Comrie and Korine Kolivras of the potential consequences of climate change for Valley Fever.[78] The Southwest report's findings are presented here.

Valley Fever and
Potential Climate Change Impacts[79]

Coccidioidomycosis, commonly known as valley fever or "cocci," is caused by *Coccidioides immitis (C. immiti*s), a fungus that grows in the soil of limited regions in the United States, as well as portions of Central and South America. Humans and other mammals, such as dogs and cattle, are susceptible to the disease. Historically, endemic regions within the United States have included Kern County in the San Joaquin Valley of California; Maricopa, Pima, and Pinal counties of Arizona; and a small portion of Texas which runs east from the southeast corner of New Mexico to slightly beyond Laredo.[80] These areas are still at risk in modern times.

There is documented evidence relating outbreaks of valley fever and climatic conditions. *C. immitis* is sensitive to climate variability, and responds to changes in moisture and temperature. Previous studies have suggested a relationship between the incidence of valley fever and climatic conditions. Temperature, precipitation, humidity, wind, and the occurrence of dust storms have been shown to affect either the growth of *C. immitis* and/or the distribution of the fungus. It is expected that the distribution of *C. immitis* and outbreaks of valley fever will be affected by climate change.

Valley fever cannot be spread from person to person, and people who have been infected with valley fever gain, in most cases, lifelong immunity to the disease.[81] The majority of the people infected (60%) either present no symptoms, or experience mild, cold-like conditions. Some may endure a variety of flu-like symptoms that usually appear after an incubation period of one to three weeks. Of those infected by *C. immiti*s, about one percent experience a disseminated form of the disease when the fungus enters the bloodstream and spreads beyond the lungs.[82] Disseminated valley fever can express itself with a wide variety of conditions. Lesions may occur on organs outside of the pulmonary system, as well as on the skin; bones and joints may be damaged. The most severe form of the disseminated disease is coccidioidal meningitis, the mortality of which is essentially one hundred percent when produced by valley fever.[83]

Valley fever is a regional disease that is likely to increase in prominence. The population of Southwestern United States is growing at a rapid pace. Many of the people who have migrated to this region are primarily from non-endemic areas, thus it is unlikely they have previously been exposed to valley fever and therefore do not have immunity to the disease. This is of particular concern in the tourist areas. If visitors were to contract a serious case of valley fever and then return home, their physicians may misdiagnose the disease.

Although most people infected with valley fever do not need to seek medical care, treatment of serious cases can be costly, both directly through medical care and indirectly, through lost worker-hours. On average, valley fever treatment in the United States costs $9 million annually, and results in a loss of almost one million person-days of labor.[84] A 1977 outbreak in California cost approximately $2 million. Another outbreak in California, which lasted from 1991 to 1994, cost an estimated $66 million in treatment, hospitalization, and lost wages.[85]

Potential Impacts of Climate Change

Precipitation and temperature appear to be the most important climatic controls on valley fever. During prolonged periods of hot, dry conditions, the surface of the soil is partially sterilized and *C. immitis* and many competing microorganisms are removed. However, *C. immitis* remains viable below the surface. When rain falls, conditions in the surface soil eventually approach the ideal for the growth of the fungus. *C. immitis* returns to the surface layer, which contains few competing organisms.[86]

Precipitation is a significant control on the distribution of *C. immitis* and incidence of valley fever. Very low rainfall, as well as annual rainfall in excess of 500 mm (20 inches), decreases the prevalence of *C. immitis* in the soil.[87] The Mohave and Sonoran Deserts of California receive approximately 76 mm (3 inches) of rain annually, too dry for *C. immitis*.[88] Coincidentally, increased rainfall at the eastern limits of the endemic zone in Texas enables competitive species to thrive.

Previous studies, conducted several decades ago, have concluded that *C. immitis* is most often found in the soil following rainy seasons, and less frequently during hot, dry periods.[89] Like-wise, studies have shown that the incidence of human infections of valley fever is highest during dry periods following the rainy season when the soil is dry and the fungus can be distributed by winds.[90]

An epidemic of valley fever in the early 1990s in California was linked to variability in precipitation. Jinadu reported that the epidemic followed five years of drought in California.[91] February and March of 1991 through 1994 had approximately double the normal amount of rainfall, and Jinadu commented that these "intense rains caused an abundant growth" of the fungus in the soil. After drying, the soil was disturbed by winds, and *C. immitis* spores were released into the air causing a much greater number of cases than normal, particularly in Kern County, California.

A study by Hugenholtz concerned the relationship between the incidence of valley fever and several climatic variables in Arizona, namely temperature, rainfall, and dust storms.[92] An examination of hospital admissions records at Williams Air Force Base in Maricopa County from 1952 to 1956, for example, showed two annual peaks in valley fever incidence, one in July and a second in October or November.[93] Months with highest incidence coincided with months having the lowest rainfall. Hugenholtz employed quantitative techniques in the study, correlating temperature, dust storm incidence, or total rainfall, with valley fever incidence. The study did not find a strong relationship between rainfall and incidence, but found stronger relationships with temperature and dust storms. Based on the findings however, Hugenholtz concluded that it is possible to predict lower infection rates during a season if the preceding wet period was drier than normal. For example, infection rates should be lower in the spring and summer following a relatively dry winter, and a drier than usual July and August should be followed by fewer infections in fall. Hugenholtz commented that his "remarks have been largely theoretical and based on an incomplete study, but they may serve to stimulate studies by other investigators."

Future Information and Research Needs

Little research examining the role of climate variability in the occurrence of valley fever has been performed since the 1950s and 1960s. Of the studies during that period, only a few com-pared climate and incidence data. In particular, the study by Hugenholtz in 1957 looked for a correlation between such information, and analyzed 14 years of data for a specific area. Although there is a general understanding of the climatic characteristics of the endemic region, the specific conditions that may result in an outbreak of valley fever are not well understood.

Although the data are in some ways problematic (given different reporting techniques and a varying incubation period), long records of valley fever incidence are available. The Southwest Regional Assessment team recommends quantitative analysis of incidence data in conjunction with climate data, such as temperature, precipitation, wind speed, and relative humidity. An analysis of the entire endemic region in the United States will allow comparisons of different climatic regimes. An analysis of climate and valley fever incidence in California can, for example, be compared to the Arizona/New Mexico region. California receives the majority of its precipitation in winter, while the Southwest experiences a bimodal precipitation pattern. The two regions therefore have differing patterns of valley fever incidence, which may provide insight into the distribution of the fungus. Analysis of multivariate climate data and valley fever incidence data can then be used to develop models of *C. immitis*' response to climate. A predictive model will be particularly useful to health care providers and government health services.

Hantavirus

Hantavirus pulmonary syndrome (HPS), like Valley Fever, is a health risk influenced by climate conditions. Though better known through outbreaks in the Four Corners area of the Southwest, Hantavirus has been a health threat in parts of California. Of the 19 cases of hantavirus identified in California, 10 resulted in fatalities.[94] The following discussion again draws on the work of the Southwest Assessment.

Hantavirus Pulmonary Syndrome
And Potential Climate Change Impacts[95]

Hantavirus was first recognized as a major threat to human health in the western hemisphere in the spring and summer of 1993, with an outbreak of disease among previously healthy populations in the Southwestern United States. Medical professionals were first warned of the disease by the deaths of a young Navajo woman and her fiancé, both healthy individuals, who died within five days of each other.[96] Three additional victims of the disease were quickly identified, all of whom had died within a few days of each other of an unidentified "rapidly progressive" respiratory illness.[97] Local health officials quickly realized a potential linkage between the five deaths, and alerted medical officers at the Centers for Disease Control and Prevention (CDC) of a possible epidemic. Intensive research and testing by the CDC and other local medical agencies traced the disease to a previously unrecognized group of New World Hantaviruses (genus Hantavirus, family Bunyaviridae).[98] Hantavirus infection is characterized by acute respiratory distress and associated symptoms including fever, chills, myalgias, and nausea,[99] with an overall case fatality rate of approximately 50%.[100]

Early cases of HPS were clustered in and around the Navajo Reservation in the Four Corners area of northwestern New Mexico and northeastern Arizona. Although not all of the victims of HPS were American Indians, fear of disease resulted in prejudicial behavior, including prohibitions against serving American Indians in restaurants and stores, unfavorable media attention, and a reference to HPS as "Navajo Flu." In reality, this clustering of HPS cases

was the result of favorable conditions for human contact with the disease and its carrier. The specific viral agent responsible for the 1993 outbreak of HPS was found to be a previously undescribed Hantavirus, Sin Nombre Virus (SNV). SNV, like other Hantaviruses, is spread by rodents. Extensive testing of rodent species in the Four Corners region (convergence of New Mexico, Arizona, Utah, and Colorado) revealed the deer mouse, *Peromyscus maniculatu*s, as the primary host for SNV. Sin Nombre Virus is transmitted to humans through inhalation of aerosolized rodent urine, feces, and saliva.[101] Activities such as gardening, hand plowing, and cleaning, especially in the rural and semi-rural areas where deer mouse populations are greatest, can result in increased risk of exposure to the Sin Nombre Virus. Conditions in the Four Corners region in the spring and summer of 1993 proved to be very favorable for an increase in rodent population density, bringing these carriers of HPS into close contact with human populations.

Potential Impacts of Climate Change

The El Niño Southern Oscillation (ENSO; commonly called El Niño) is a cyclical climatic phenomenon that results in a large-scale weakening of the trade winds, warming of the surface layers of the tropical Pacific Ocean, and increased rainfall across the southern regions of the United States. El Niño events occur irregularly at intervals of 2 to 7 years. In 1991 and 1992 the Southwestern United States experienced warmer than average winters and atypically heavy rainfall as a result of ENSO. The effects of these environmental fluctuations were especially pronounced, because the Southwest had for the previous six years experienced drought conditions.[102] It has been proposed that the result of the El Niño phenomenon was to increase vegetation growth in the Four Corners region, causing a dramatic explosion in rodent populations in response to the greater availability of food resources. Specifically, rodent populations reacted to an abundance of piñon seeds in the winter season and grass seeds in the spring season.[103] The ENSO event amplified the risk of zoonotic (animal to human) transmission of HPS by bringing host populations into closer contact with humans. Estimates of the abundance of deer mice following the ENSO event suggest that rodent populations were 10 to 15 times higher than average,[104] and that the origins of the 1993 outbreak of HPS may be traced to this abundance.[105]

Future Information and Research Needs

The relationship between climatic variability and incidence of HPS can be examined through analysis of factors that may influence fluctuations in rodent populations, such as vegetation density, precipitation, temperature, and elevation. These data may be obtained from satellite-based remote sensors, which collect data at regular intervals over large areas. Other sources of data include ground-based precipitation and weather monitoring stations, global positioning systems, and vegetation surveys.[106]

The California Department of Health Services notes that:[107]

> The only rodent in California that is known to transmit the virus is the deermouse *(Peromyscus maniculatu*s). It is 4 to 7 inches long from head to tail, grey to brown in color with white fur on the belly and underside of tail, and has large ears. Infectious deermice do not appear to show any signs of illness. There is no way to tell an infected rodent from a non-infected rodent just by looking at it. It is also sometimes difficult to tell deermice from other rodents.

Encephalitides

William Reisen provides a summary of the issues surrounding mosquito vectors for Encephalitides.

Effects of Climate Variation on the Mosquito-Borne Encephalitides of California

William K. Reisen
Arbovirus Field Station
Bakersfield, CA

Western equine encephalomyelitis and St. Louis encephalitis are arboviruses of public health and veterinary concern in California. These viruses are maintained in enzootic transmission cycles comprised of the primary mosquito vector *Culex tarsalis* and several avian reservoirs (especially the house finch).[108] Human and equine infection occurs tangentially to the primary enzootic cycle, and these are a dead end hosts for the virus because they do not produce sufficient virus to infect additional mosquitoes. Virus dynamics and therefore health risks are strongly dependent upon the population dynamics, size and susceptibility of vector and vertebrate host populations. Because vertebrate hosts experience a short-termed acute infection when they are viremic and able to infect mosquitoes, most of the virus maintenance cycle is spent within the mosquito host. Mosquitoes are poikilotherms (cold blooded animals), and their body temperature and virus infections approximate ambient conditions. In general temperatures affect the rate and timing of biological functions, whereas water affects population size.[109]

Warm temperatures increase whereas cold temperatures decrease the rate of biological functions. Therefore, warming temperatures increase the rate of mosquito development from egg to adult, decrease population generation time and increase population growth rate.[110] Virus replication within the mosquito host also progresses faster at warmer temperatures, decreasing the time required from infection to transmission.[111] Hot temperatures and decreasing humidity tend to decrease mosquito life expectancy at emergence and may negatively impact adult population size.[112] Although the duration of infective life is shortened by elevated temperature, this is compensated by the increase in the extrinsic incubation rate of the virus in the mosquito host and encephalitis viruses tend to be transmitted most effectively during warm summer months. Because the vertebrate hosts are homeotherms (constant body temperature), ambient temperatures have minimal impact of virus infections.

Wet years generally increase the amount of suitable mosquito habitat and therefore increase mosquito population size.[113] Urban *Culex* mosquitoes that develop in storm water channels contradict this general rule and maybe most abundant during dry years when spates fail to scour drainage systems and allow the pooling of water and organic material. Increased growth of food plants and associated insects during wet years increase avian reproductive success and therefore population recruitment and size. The addition of susceptible hatching year birds during summer facilitates transmission. Increased mosquito and host population size generally results in increased transmission rates and therefore the risk of human and equine infection.

Retrospective analysis indicates that WEE virus frequently becomes active during cool wet El Nino years when vector abundance is elevated, whereas SLE virus tends to appear during hot dry La Nina years when hot summer temperatures facilitate transmission by reducing the extrinsic incubation period. On-going research is evaluating the use of these changes in climate in forecasting the risk of encephalitis virus activity.

What is this man holding? The image is of just *one night's catch* of mosquitoes at a trap in the Coachella Valley.

Coachella Valley in 1995, William K. Reisen

Summary

Direct and indirect impacts to human health may result from climate change. It is clear that heat waves and other extreme events pose serious public health concerns. Secondary or indirect effects of changes in climate may pose less obvious concerns such as changes in disease vectors. A comprehensive study of the potential implications of climate change and variability for human health in California would improve our understanding of the issue.

The summary findings of the Pew study are applicable for California: [114]

- Higher temperatures are likely to negatively affect health by exacerbating air pollution and increasing the occurrence of heat waves. The elderly, infirm, and poor are most at risk because these conditions can exacerbate pre-existing disease. Lack of access to air conditioning increases the risk of heat-related illness.

- While there is some indication that changing climatic conditions may increase the risk of vector- and water-borne diseases, sanitation and public health system

infrastructures in the United States should prevent these diseases from becoming widespread. To prevent such out-breaks, it is vital that we take steps to maintain and strengthen these infrastructures, including increased surveillance and vector control. At the same time, global health impacts from infectious diseases will almost certainly be greater, as many countries lack either the resources and/or infrastructures to protect their populations.

- Uncertainty about adverse health effects should not be interpreted as certainty of no adverse health effects. Moreover, the potential for unexpected events — e.g., sudden changes in climate or the emergence of new diseases — cannot be ruled out.

Maintenance and strengthening of public health infrastructure, especially surveillance and vector control, will be critical to preventing significant outbreaks in the future. Inclusion of public health and climate change experts in planning regarding land-use and utility infrastructure will also help assure maximal protection of public health during this upcoming period of climate change.[115]

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V. Response Strategies: Building Resilience in Systems

Developing Informed and Systematic Response Strategies

Scientific research indicates that climate change is real and that it is already occurring. There is, therefore, a need to consider coping and adaptation strategies as directed by the USGCRP. This assessment focuses on various ways in which California can build resilience to cope and adapt to the impacts of climate change and variability. In particular, it examines "no regrets" and "multiple benefits" strategies that address existing stresses and opportunities in the context of a changing climate.

A Systematic Approach to Responses

The IPCC identified three terms and concepts which should be considered: sensitivity, adaptability, and vulnerability. Each term and concept is important to both private and public sector investment and planning:[1]

> **Sensitivity** is the degree to which a system will respond to a change in conditions.
>
> **Adaptability** refers to the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes. (Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of changes in conditions.)
>
> **Vulnerability** defines the extent to which change may damage or harm a system. (It depends not only on a system's *sensitivity* but also on its ability to *adapt* to new conditions.)

Note that the focus is on *systems*. As this assessment has outlined, the economic activities, physical infrastructure, and natural systems in California are inextricably linked. A good understanding of the dynamics of these systems is essential, as is a clear sense of their interrelationships. These concepts apply as much to business enterprises as they do to ecosystems. In considering appropriate strategies to deal with climate change, whether they are labeled "response" or "coping" or "adaptation", we must consider the nexus between sensitivity to changes, capacity to change or adapt, and vulnerability to change. These factors will inform cost/benefit estimates and the social and political assessment of acceptability of risk. Ultimate action on responses will also be driven by a sense of ethical and moral duty. As recent environmental policy decisions indicate (in both the courts and the legislative bodies of the state and federal government), people do seem to care about future generations and other species.

Kelly Redmond at the Desert Research Institute made the following observation in this regard: [2]

> While physical scientists debate whether changes are taking place in the climate system, other changes are taking place in the societal value system. Views have increasingly migrated toward favoring free-running rivers, less reliance on structural solutions to flood problems, and greater reliance on behavioral solutions, such as staying off the flood plain and de-emphasizing the placement of permanent and valuable structures there.

He is correct. The goal of California decision-makers and stakeholders should therefore be to craft investment and policy strategies to maintain ecosystem health, productive capacity, and quality of life within the framework of the concerns and values of the region. These decisions should in turn be based on an accurate scientific understanding of the issues. To the extent that we are learning and living by "adaptive" management, we need to maximize the level of resilience in systems.

A priority for on-going research and collaborative efforts in the region will be to better understand and define the *degree of sensitivity* of key systems (natural and human) to climate change and variability, the *potential for adaptability*, and *the vulnerability of these systems*. We can then plan for change and preserve the values we cherish in this unique region of the world.

"No Regrets" and "Multiple Benefit" Strategies

Many of the strategies included in this section will improve our ability to deal with *existing* stresses and problems. These are often characterized as "no regrets" strategies because they involve measures that make sense regardless of the way climate change impacts the region. Where possible, we should seek to secure multiple benefits through well-designed policies, investments, and strategies. The focus is to build resilience in various systems in California, from water supply to building designs. It should be acknowledged at the outset, however, that some impacts may be beyond our ability to adapt to.

No Regrets Strategies

A number of cost-effective "no regrets" and "multiple benefits" strategies are available to address more than one objective through targeted investments and policy measures. These strategies can enhance performance and build resilience *regardless* of how climate change unfolds. This is why they are called "no regrets" strategies. For example, improving the efficiency of resource use by reducing waste makes good sense regardless of climate change. Likewise, designing policies and management systems to provide better signals to consumers regarding the cost and scarcity of resources is a useful thing to do with or without climate change. Multiple benefits are possible from strategies such as flood plain management approaches that reduce damage from flooding, provide habitat, and increase groundwater recharge during high precipitation events. These are all measures that provide important benefits regardless of how the climate may change.

The Multiple Benefits Logic

Typically we focus on accounting for specific costs of a project or program, and then we compare those costs against a specific benefit. We often fail to account for, let alone take credit for, other important benefits that accrue from a well-planned investment that solves for multiple objectives. With a focus on *multiple benefits*, we account for the various goals achieved through a single investment. As over 2,600 economists, including eight Nobel Laureates in economics, have formally stated: *Policy options exist that would slow climate change without harming American living standards, and these measures may in fact improve U.S. productivity in the longer run.*[3]

The Art of the Long View: Creating Scenarios for Alternative California Futures

The California regional assessment effort has been fortunate to have the active participation of business leaders and some of the world's leading business strategists. Peter Schwartz, President of the Global Business Network, provided a keynote presentation at the California workshop in which he made a number of important points including:[4]

> It is becoming increasingly important to consider environmental forces and their implications for the future of business and society. *California will have to add climate change and variability into all planning processes in order to avoid surprises.*

Schwartz also focused explicitly on the issue of sustainability.

> The question of sustainability is one that must be addressed in building scenarios. Since the industrial revolution, mechanized industrial production, increased natural resource use, and improvements in health care and consequent rise in population have placed numerous and growing stresses on the natural environment. As the 21st century approaches, the world is experiencing a global population that has tripled in this century, with startling consequences: steadily expanding land use; loss of biodiversity; a rate and scale of natural resource consumption that in hundreds of years has led to the depletion of stocks that took tens of thousands or even millions of years to accumulate; degradation of the quality of air, water, and land, and anthropogenic climate change.

Ecosystems and natural processes are increasingly recognized for providing significant value to the state.[5] As a number of the California's business leaders, senior state officials, and NGOs in the California Environmental Dialogue observe: [6]

> The interdependence of the economy and environment is at the foundation of California's wealth and at the center of the California dream. … California's habitats and natural communities are an integral part of the economic foundation upon which future prosperity depends. …we need an expanded public/private natural resource investment strategy to restore life-supporting habitats and fully protect vital natural systems.

To cope and adapt effectively, efficiently, and equitably, we will need to better understand the dynamics of the systems of concern and our options and opportunities. A critical first step is to build an improved understanding of the science by the public and decision-makers.

Public Education

A recurring theme in discussions and meetings on the potential impacts of climate change is the need for public education. John Fialka, lead writer for the *Wall Street Journal*, gave a keynote address for the California workshop. His assignment was to provide an even-handed overview of the Kyoto process. He did a masterful job with his assignment, and then he moved on to a much more important subject: public education and individual responsibility. He told a story of personal experience in building an understanding of ecological systems and of the problem of people who either fail to learn, of don't care. Among his points:

> Underlying much of the opposition in this country is a lack of scientific comprehension that would enable people to understand the problems and the risks of climate change, and how they contribute to them, and how they can minimize them.
>
> Climate change is a grassroots problem, but the people who understand the problem and its potential consequences—primarily scientists, academics, and science journalists—haven't done a good job of educating the public and politicians.

Fialka's admonition was clear and to the point. One of the work groups at the workshop focused on the issue of public education and produced the following recommendations:[7]

1. The flow of scientific information to the public should be institutionalized and sustained, just as the public has committed long-term funding to climate science research. Reciprocity between the taxpayer and the climate science community is essential to:
    - Provide the public with a return on its tax dollar investment.
    - Maintain public support for continuing climate science research.

2. The information flow should be formalized as a Local Climate Information and Response Program (LCIRP) to:

- Package simply, visually, and forcefully the climate science
- Portray dynamically and factually the range of local impact scenarios
- Document success stories from other response strategies implemented around the country; “give folks a way out. . .”
- Build a sustained and two-way dialog between the public and the science communities.
- Clarify for individuals, wherever they plug into a community's fabric, that climate change is happening “on their watch.” Their contributions to climate change are personal; their efforts to reduce their impact footprints can make a difference. In fact, the only thing that will make a difference is personal action motivated by a renewed sense of personal and community stewardship.
- Build a media/outreach plan into each grant. These program elements should meet some performance for interaction beyond the normal university/college boundaries to involve those doing the science with those paying for it.
- Capitalize on the “here, now, credible” experience of prediction and public awareness demonstrated for the current El Niño. Integrate the lessons learned of coastal and island communities in dealing with climate change and variability.

3. A strong LCIRP element should be a proactive engagement with professional organizations from every sector of our socio-economic domain. These include churches, engineering, women’s professional, environmental, planning, and a wide range of other organization types.

4. The potential costs of *not* responding proactively to climate change vis-à-vis the costs of a default stand-by response mode need to be quantified, publicized, and debated. They will differ for nearly every community. Getting this discussed locally is a proven way of involving people as it involves their money.

5. LCIRP activities should commence immediately. There is value in the communication inertia and local awareness produced by this activity. A parallel research agenda should be initiated to:
    - Identify methodologies by which the mega-issues of our time can be communicated to ordinary people in meaningful ways which initiate informed response measures.
    - Identify optimum processes and suitable communication technologies to accomplish LCIRP.
    - Determine an appropriate mix of methodologies, processes, and technologies for a range of community types by region, economic base, ethnic and cultural mix, and local values/traditions. These are only a few of the factors which must be respected in bringing credible, outside, and complex information to new places.

The Southwest Assessment reached a similar conclusion: [8]

> Coping with the consequences of climate variability and climate change requires development of a suite of complementary and coordinated strategies. One of these

strategies is public education about how climate affects their lives and livelihoods, both positively and negatively.

As part of the California regional assessment, dozens of presentations have been made on the potential impacts of climate change and variability.[9] Though there is much to be done, a number of encouraging signs are present.

Experts and Professional Groups are Paying Attention

Several important and useful steps toward building broader public understanding of the issue can be reported. Following the USGCRP California Regional Workshop,[10] the Water Education Foundation published a well-written special issue of *Western Water* on "Climate Change and Water: What Might the Future Hold?"[11] This widely read and respected publication is an excellent vehicle for providing information to both professional and interested lay audiences. Other positive developments include regular inclusion of climate change issues in major water policy conferences in California over the past several years.

Policymakers have indicated a growing interest in understanding the potential impacts of climate change. Meetings with other key institutions and stakeholders dealing with water issues include: the Metropolitan Water District of Southern California (MWD), California Resources Agency, California Department of Water Resources, California Continuing Resource Investment Strategy Program (CCRISP), California EPA, California Office of Environmental Health Hazard Assessment, the Western Governors' Association, various businesses, farmers, major landowners, environmental organizations, and the Society for Ecological Restoration.

California Decision-Makers are Listening

Another positive development in the area of public education involves key decisions-makers. Senate and Assembly committee hearings on the impacts of climate change were held in 2001. The Select Committee on Delta Resources and Development of the California Senate, chaired by Senator Machado, held hearings in Sacramento in November, 2001 on *Global Climate Change and Its Potential Effects on the Sacramento-San Joaquin Delta*. The Select Committee on Air and Water Quality of the California Assembly, chaired by Assemblywoman Fran Pavley, also held hearings in November, 2001 on *Potential Impacts of Global Climate Change and Variability on California*. Both hearings were well attended by the public, government agencies, and others interested in the issue.

The Secretary of Resources has established an inter-agency climate change task force to address issues facing the state, and the California Energy Commission, through its Public Interest Energy Research program, is investing significant resources in climate change research.

It is reasonable to conclude that public interest in the issue of climate change, and specifically with regard to water resource issues, is increasing rapidly. The California Department of Water

Resources has recently determined that the issue merits a full chapter in the state's official water plan, another useful way to provide information to the public.

Public Information: Response Strategies for Extreme Heat Conditions

The National Weather Service has developed a heat index to assist people to understand the risks and conditions associated with high temperatures. Further information is available at the NOAA web site.

NOAA's National Weather Service
Heat Index Program[12]

About 175 Americans are killed by heat waves. Considering this tragic death toll, the National Weather Service (NWS) has stepped up its efforts to alert more effectively the general public and appropriate authorities to the hazards of heat waves-those prolonged excessive heat/humidity episodes.

Based on the latest research findings, the NWS has devised the "Heat Index" (HI), (sometimes referred to as the "apparent temperature"). The HI, given in degrees F, is an accurate measure of how hot it really feels when relative humidity (RH) is added to the actual air temperature. As an example, if the air temperature is 95°F and the RH is 55%, the HI-or how hot it really feels – is 110°F. (For a chart see: http://www.nws.noaa.gov/om/brochures/heatwave.pdf) (Since HI values were devised for shady, light wind conditions, EXPOSURE TO FULL SUNSHINE CAN INCREASE HI VALUES BY UP TO 15°F. Also, STRONG WINDS, PARTICULARLY WITH VERY HOT, DRY AIR, CAN BE EXTREMELY HAZARDOUS.)

Summary of NWS's Alert Procedures

The NWS will initiate alert procedures when the HI is expected to exceed 105°- 1 10°F (depending on local climate) for at least two consecutive days.

The procedures are:

- Include HI values in zone and city forecasts.
- Issue Special Weather Statements and/or Public
- Information Statements presenting a detailed discussion of (1) the extent of the hazard including HI values, (2) who is most at risk, (3) safety rules for reducing the risk.
- Assist state/local health officials in preparing Civil Emergency Messages in severe heat waves. Meteorological information from Special Weather Statements will be included as well as more detailed medical information, advice, and names and telephone numbers of health officials.
- Release to the media and over NOAA's own Weather Radio all of the above information.

The following websites provide additional information on air quality:[13]

Criteria air pollutants and toxic air contaminants: www.arb.ca.gov/aqd/almanac01/almanac01.htm
Air pollution and health: www.arbis.arb.ca.gov/research/health/fs/fs.htm
Visibility: www.arb.ca.gov/planning/reghaze/reghaze.htm
Indoor air quality: www.arb.ca.gov/research/indoor/indoor.htm

California Pilot Project on the Use of Climate Forecast Information (NOAA)

During the most recent El Niño, NOAA established a highly successful pilot program to provide scientific information to key users. All of the information was open and available to the public. NOAA recognized, however, that not everyone was getting the information they needed. The pilot project aimed to help get the information to decision-makers who needed it.

Ants Leetmaa, Director, Climate Prediction Center, NOAA, chaired a session at the California regional workshop to review the lessons learned from the program. The following summary was provided by Claudia Nierenberg, Economist, Office of Global Programs, NOAA.[14]

Scientists and agencies need to package information in useful and understandable forms and provide it at the right times (this will be different for different users). This will require continuing dialogue between providers and users—including feedback on the forecast products and how they are being used and identification of information needs. This information must be timely and updateable–a continuum of information from climate outlooks to real-time data.

There is a need to:

- recognize the value of a proactive approach, rather than reacting to crises.
- share new forms of collaboration and information.
- develop credibility/trust in longer-range forecasts; this will be a slow process of education.
- interpret forecasts and work with users to learn what forms of forecast information are understandable and usable.

Examples of forecast use:

1. Orange County Sanitation didn't know where to look at El Niño data when preparation and planning for the storms began (or should have begun).
    - Three-to-five day forecasts were not far out enough, so when they learned about weekly threats assessment (in December 1997), they began to use it.
    - They were becoming aware of what is available through dialogue. Now that we know the information is there, we will continue to use it (can use forecasts as much as a year in advance and weekly threat assessments). Three-to-five day forecasts and real-time data will be altered as time goes on.

2. William Mumbleau, information and technology services for Los Angeles County Metropolitan Transportation Authority, went into 'high activation mode' last year (as El Niño warnings were being publicized), although management was saying "wait till raindrops hit." He saw the value of proactive vs. reactive (crisis driven) response. For example, he anticipated increase in maintenance costs for buses due to flooding damage to bus batteries.

    - He started by trying to find out where data is

- Information must be timely and updateable, it must be integrated. How the data is packaged is very important. Information must be shared and disseminated to users as well as to the scientific community (to do impact assessments).

3. Department of Water Resources' use of short-range forecasts (five-to-ten days) depends on the staff meteorologist. (This year, for example, use of CDC long-range forecast: river runoff projections at start of year looking at/for periods of exceedance, regular updates are important, longer-term forecasts must demonstrate their credibility.)

    - Need information on the probability distributions (especially on the dry side which is where farmers and operators must hedge their bets).

    - This year's precipitation patterns (1998) in the Sierra seems to be similar to 1982-83; patterns not at all like 1996-97 when the rainfall was mostly coastal. Snowdepth also seems to look like 1982-83.

In each of these cases, and a number of others, NOAA's efforts led to improved dissemination of information to users. The general lesson for this assessment is that increased efforts to understand what information people need, and in what forms, will improve the effective use of it.

Restoring Ecosystems and Building Resilience

Ecosystems respond to climate change in various ways. The composition of species may shift, and ecosystem functions may change as temperature, moisture, and other factors are altered. The results may or may not be desirable from an anthropogenic perspective. As Rebecca Shaw notes:[15]

> Climate change is not a new phenomenon. In the past 2.6 million years, the Earth has experienced a succession of glacial and interglacial cycles that have resulted in large fluctuations in climate. Ecosystems have responded to these dramatic climatic shifts through redistributions of species, changes in species diversity and modifications of ecosystem functions. Because other environmental factors influence species distributions (e.g. soil types and inter-specific interactions), the persistence of ecosystems and survival of species under a changing climate is not merely a function of migration to the climatic conditions ideal for growth. In order for ecosystems and species assemblages to be maintained, there must be time for adaptation to a new set of conditions. Past climate changes have occurred over hundreds of years, allowing time for most ecosystems to adapt gradually and for many species to migrate to locations suitable for growth and regeneration.

Maintaining species diversity and supporting viable, healthy ecosystems is a policy and management goal in California and in the United States. There are approaches to restoring these systems that will build resilience and the capacity to cope and adapt to climate change. Marten Scheffer et al. argue that the focus of management efforts should be on building resilience:[16]

> All ecosystems are exposed to gradual changes in climate, nutrient loading, habitat fragmentation or biotic exploitation. Nature is usually assumed to respond to gradual change in a smooth way. However, studies on lakes, coral reefs, oceans, forests and arid lands have shown that smooth change can be interrupted by sudden drastic switches to a contrasting state. Although diverse events can trigger such shifts, recent studies show that a loss of resilience usually paves the way for a switch to an alternative state. This suggests that strategies for sustainable management of such ecosystems should focus on maintaining resilience.

Field et al. identified three potential responses of ecosystems:

Response of Ecosystems to Climate Change[17]

Potential responses of California ecosystems to climate change fall generally into three interrelated categories:

Geographic: the boundaries between ecosystem types will move and the character of landscapes will inevitably change along with shifts in climate.

Processes: the responses may involve changes in the way ecological processes work and in the goods and services that ecosystems supply to human societies (such as purification of air and water, decomposition of wastes, maintenance of soil fertility, control of pests, pollination services, recreational opportunities, plant productivity, the health of fisheries).

Species and Communities: changes in the kinds of plants and animals that live in a community, and these necessarily lead to changes in how the ecosystem works.

For various reasons we may wish to influence the ability of ecosystems and species to adapt to climate change. Moral and ethical concerns and values underpin laws protecting threatened and endangered species. Practical economic considerations also provide an impetus to develop strategies for these systems.

Several strong themes emerge from the scientific literature on ecosystems and the potential implications of climate change. The first is that existing stresses caused by water diversions, land-use, pollution of various kinds, and other factors is stressing both ecosystems and individual species. Reduction of these stressors will enhance the ability of ecosystems and species to cope and adapt to change – regardless of the cause. Second, habitat is limited and fragmented. As Field et al. point out it: "endangered plants and animals will not be protected against climate change unless we make a concerted effort to physically link isolated reserves and to keep suitable migration corridors open."[18] "Of 194 plant community types mapped by the California Gap Analysis Project, more than a third (73 types) have less than 10% of their current distribution in reserves. Over 1,000 individual reserves are less than 500 acres in size."[19]

Researchers conclude that "modest investments now can help secure both ecological and economic options over many future generations."[20] Field et al. provide the following recommendations for action:

Recommended Actions for Ecosystems[21]

- Limiting the footprint of development on the landscape, particularly in vulnerable habitats such as wetlands and areas subject to fires, floods, and landslides, is probably the most important action Californians can take.
- Limiting the area of human infrastructure can preserve habitat, maximize the size of habitat patches, and avoid severing the connections among natural areas in the landscape.
- Restoring degraded habitats can also be a vital complement to limiting the footprint of development.
- In California's coastal marine and freshwater eco-systems, effective actions include minimizing inputs of waste products while minimizing extractions of water from streams and rivers.
- Strategies such as managing the dynamics of water releases from dams can contribute to lowering overall human impacts.
- Nature reserves should be designed to accommodate future climate changes and necessary range shifts and migrations of plants and animals. Design improvements could include larger size, layouts that encompass a greater range of local habitats and environmental conditions, and locations that maintain or enhance connectivity among habitat remnants.
- Marine reserves should be designated and managed in tandem with protected areas on land to reflect the vital links between healthy watersheds and wetlands and the continued productivity of coastal waters.
- Restoration ecology is making major strides in developing theory and practice to support rehabilitation of degraded ecosystems, especially wetlands.[22] As this field advances, it will be increasingly possible to use such ecological engineering to help ameliorate the impacts of climate change. It is too early to know whether these efforts should include deliberately moving species or entire ecosystems.
- Restoration should be viewed as one component of a larger picture, used to reverse damage rather than to justify further damage to California ecosystems.
- Limiting and controlling biological invasions should be a top priority. The overwhelming evidence on invaders is that they degrade ecosystems and displace native species. Without dedicated action, the negative impacts of biological invaders will increase as the climate changes.
- Learning to recognize and fairly value the many subsidies and services our society receives from healthy ecosystems will help to ensure their protection in the face of a changing climate. Human societies preserve and protect what they value, and nature's subsidies in the form of pure air and water, fertile soil, and rich and productive ecosystems have been taken for granted too long. By acknowledging the economic and societal value of the services we receive from natural and managed ecosystems, we will be able to assign more realistic priorities to stabilizing and nurturing these systems in the face of climate change.[23]
- Finally, it is important to take the long view. Climate change and ecosystem responses to it will unfold rapidly in relation to the history of the earth but may seem slow in relation to human perceptions. Humans and human societies can adjust to a broad range of physical and ecological environments. The adjustments generally involve costs as well as benefits. As we face the prospect of climate-driven ecological changes that may persist for centuries, it is worth taking time to consider seriously how modest investments over the next few years might secure both our ecological and economic options for many generations.

An Evolving Focus on Multiple-Factor Risk Assessments and Regulatory Strategies

Boesch et al. note that "the National Research Council, in its 1994 assessment of priorities for coastal ecosystem science, concluded that the paradigm of single-factor risk assessment is gradually shifting to one in which multiple-factor risk assessments and regulatory strategies take a broader range of impacts into account. These include indirect, cascading, and scale-related effects, such as eutrophication, hydrodynamic modifications, and losses of biodiversity, which increasingly require an ecosystem perspective."[24]

A lack of coherent strategy of governance complicates response strategies. As the coastal sector report notes:[25]

> The United States generally continues to manage oceans and coastal resources on a "sector by sector" basis.[26] Such an approach often fails to account for these cumulative impacts to resources, especially as individual users and interest groups have become more defensive about the benefits they obtain from coastal waters. While much remains to be learned in order to confidently project impacts of climate change on coastal areas and marine resources, the trends and relationships already apparent suggest that the managers, decision-makers and the public must take climate change impacts into account in policies and plans. To be successful, this will have to be done in the context of coastal and resource management challenges already being addressed.
>
> With few exceptions, the potential consequences of climate change are not yet being considered in a management context, despite the fact that it has been shown that planning protection or retreat strategies for coastal developments can substantially reduce the economic impacts of inundation and shoreline migration.[27]

Field et al. identified multiple-benefits strategies as an opportunity for policy: [28]

> The steps that will provide the greatest protection for California's ecosystems from avoidable damage during climate change will also yield positive benefits for public safety, recreation, agriculture, fisheries, and our unique natural heritage—even without significant changes to the climate. One key step involves limiting the footprint of development on the landscape, particularly in vulnerable habitats such as wetlands and areas subject to fires, floods, and landslides.

The next section turns to that footprint and the built infrastructure.

Building Resilience in the Urban Infrastructure

Land-Use Planning and Design

> *Existing patterns of urban and suburban development seriously impair our quality of life. The symptoms are: more congestion and air pollution resulting from our increased dependence on automobiles, the loss of precious open space, the need for costly improvements to roads and public services, the inequitable distribution of economic resources, and the loss of a sense of community. By drawing upon the best from the past and the present, we can plan communities that will more successfully serve the needs of those who live and work within them.*
>
> Preamble to the Ahwahnee Principles[29]

One of the best examples of integrated design and land-use planning is Village Homes in Davis, California. The project demonstrates the potential for securing multiple benefits including reductions in greenhouse gas emissions.

More than 25 years ago, Michael and Judy Corbett purchased 60 acres of farmland west of Davis and set out to create a community around the needs of people, not cars. The community they designed incorporated energy efficiency, natural drainage, common greenbelts, agricultural areas, commercial space, community facilities, and a network of pedestrian paths. Overcoming skepticism about "green" projects and opposition to the unconventional approach to the development, the Corbetts were finally able to realize their vision. Not only is it an economic success, Village Homes is a development that fosters a sense of community.

Village Homes consists of 220 single-family homes and 20 apartments. Some 650 people live in the community. One-quarter of the 60 acre development is set aside for open space, community agriculture, and recreation areas. Among the features that were incorporated in to the development are pedestrian corridors, bikepaths, and narrow streets that encourage alternative transportation. Residents use 36% less energy for vehicular driving[30] than people in similar neighborhoods that were not designed with sustainable principles in mind. The tree-lined narrow streets minimize the heat absorption in the area, reducing the average temperatures as much as 10 percent and hence the need for air conditioning during the hot Central Valley summers. Energy efficiency designs in the homes result in a nearly 50% reduction in electricity use, and almost one third less natural gas than conventional homes.[31]

The sense of community in Village Homes is nurtured by the open spaces, a swimming pool, and a child-care cooperative. A homeowner's association manages the income-producing apartments and office building as well as the harvesting and distribution of fruits and nuts.

Perhaps one of the most convincing successes of the Village Homes project is the fact that home values are on average $11 per square foot higher than in similar surrounding neighborhoods. The amenities of the development have proved to be of value. People want energy efficiency, open space, and the community atmosphere provided here.

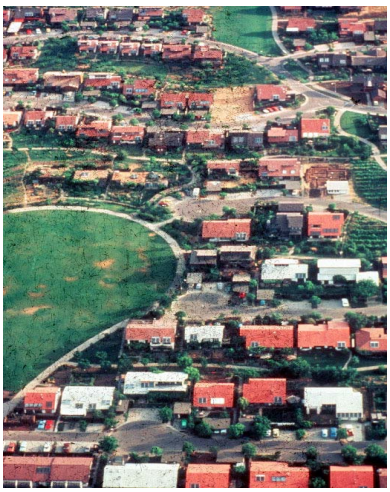
This section on land-use planning is followed by a discussion of green building strategies.

Village Homes Blends Urban Lifestyle and Environmentally Sound Planning into a Diverse, Livable Neighborhood

Local Government Commission[32]

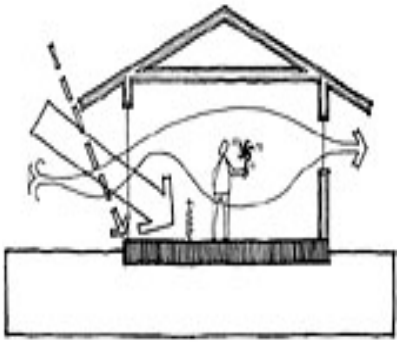
Village Homes is a planned unit development of single-family homes, apartments, a community center and office building on a 60-acre site in Davis, California. Located fourteen miles west of the state's capital city, Sacramento, Village Homes features solar water and space heating, natural cooling systems, agricultural areas and greenbelts, cooperative maintenance of common areas, a well-used bicycle and pedestrian path network, and a natural drainage system.

The project serves as a national model for environmentally sustainable development, energy-conserving planning, architecture and engineering, and community planning. Energy consumption is one-third to one-half that of neighboring development. Homes sold quickly when the development was first built. Initially, prices were the same as in neighboring developments. Today, homes sell for $11/sq. ft. more and sell in half the time as others in Davis.



Environmental Focus: Natural Heating & Cooling

North-South Orientation. All houses are oriented toward the south, accommodating the use of solar panels. This design also allows south facing windows to be shaded in the summer by an overhang and to take advantage of the low winter sun for space heating. Passive Heating and Cooling. Homes are well-insulated and incorporate thermal mass. The mass absorbs excessive heat during the day and dissipates it at night when temperatures drop. Most windows are south facing with overhangs that shade the windows in the summer and allow sun to penetrate the house in the winter.



Energy consumption in Village Homes is much lower than that of surrounding areas – with annual kilowatt/hour per capita of 7,320 compared to 12,069 in outlying vicinities. Solar Hot Water Systems. Solar systems in Davis, CA, can meet 100% of a home's hot water needs in the summer and at least 50% in the winter. A natural thermosiphon system warms water in a flat plate collector as it rises to an insulated storage tank. No pumps or controls are necessary.

Landscaping. Roads are narrow and shaded by deciduous trees, which allows the streets to be shaded in the summer, reducing the ambient temperature by 10 degrees. Homes stay cool without air conditioning despite the hot summer climate.

Implementing the Plan

The development was proposed by the developer as a Planned Unit Development. The plan evolved over several years as the developer worked to respond to perceived needs for a greater sense of community and an ecologically sound lifestyle.

Greenbelts and community facilities were designed by the developer. Residents assisted in their construction during the weekend work parties. Common areas shared by clusters of eight homes were landscaped by the developer who then gave residents of each cluster $600 to customize the space. Lots were developed at a rate of about 50 per year over a five-year period. Each unit sold within 12 months. Partners earned 23% per annum on their investment. Five houses were built using sweat equity.

An aerial view of Village Homes shows walking and bicycling paths. Note that there are no dividing fences, leaving residents less than one minute to the nearest park and only three minutes from the community center.

The results of these design features? The average person knows 42 people in their neighborhood, compared to 17 by those in outlying areas. Residents spend 3.5 hours a week with friends in the neighborhood, compared to a vicinity average of 0.9 hrs./week. The average resident identifies 4.0 of their best friends living within the neighborhood, while the average is 0.4 for people living elsewhere in the vicinity.

A Strong, Nurturing Community Life

Community Building. Rather than relying on city parks and recreational facilities, Village Homes contains its own facilities. A swimming pool and community building, two "village greens," and two playgrounds offer places where neighbors can socialize and kids can play safely. Common areas shared by clusters of eight homes provide places for immediate neighbors to meet.

The residents also have administrative reasons to come together. The neighborhood makes management and financial decisions regarding the maintenance of open space and recreational facilities, the harvesting and distribution of fruits and nuts, the income-producing office space and apartment units, and new planning developments. The process of carrying out these decisions also enriches the interaction among neighbors.

Self-Government. Residents maintain all agricultural lands, own the major building complexes and apartment units, and control future development themselves through their homeowners' association.

Supportive Environment for Children. The children of Village Homes can safely explore their own environment (not restricted to their own small block) and have the opportunity to develop social relationships among a broad spectrum of people. The daycare center is a safe walk away for every child in the neighborhood.

Rural Atmosphere. In addition to community gardens, mini-orchards and vineyards, there are common areas adjacent to every house used for growing fruits and vegetables. A homeowners' committee determines how fruits and nuts are picked and distributed. In addition to providing food, residents are directly involved in the decision-making, thus fostering interaction between neighbors.

Reduced Living Costs. With lower utility bills, a reduced need for the automobile, and the ability to grow most of your own fruits and vegetables, homeowners have an opportunity to be more self-sufficient.

Economic Sustainability

The office building, apartments and community building a Village Homes are owned and operated by the homeowners' association - producing a substantial amount of income. The neighborhood is adjacent to its largest

employer, the University of California at Davis. Off-street bicycle paths run from every home to the campus center. There are also job opportunities within the neighborhood through employment by the homeowners' association, at the neighborhood office building and the daycare center. Several entrepreneurs have used the agricultural lands to earn a living by growing and selling fruits and vegetables.

A Healthy Environment

Healthy environments emphasize elements that improve our well-being while minimizing the sources of emotional and physical stress. Accentuate the Positive: Walking and bicycling paths link all sites. Rich and dense foliage of trees are generously planted throughout. Communal areas and activities are prevalent, and there are many places for children to play. Fresh fruits and vegetables are everywhere. Eliminate the Negative: Narrow streets inhibit speeding cars. Fenced backyards are replaced by common areas. With houses oriented toward the common areas, crime is less of a concern.

Village Homes' pedestrian-oriented plan increases the opportunity for large amounts of open space through compact and efficient land use, and reduces vehicle trips and auto emissions. The average walking distance to the grocery store is approximately 10 minutes, and 4.6 minutes to the on-site office buildings.

Creating Land-Use Diversity

Housing Blend. The mix of housing types allows a diverse population to form a vibrant community. There are 220 individual homes and 20 apartments. Sizes range from 3,000 sq. ft. to a cluster of 600 sq.-ft. units with a shared community room. A co-op house accommodates a dozen people in a nine-bedroom house.

Mobility Network. Walking, biking, and driving are all supported with networks that traverse the entire neighborhood. There are more walking and bicycling paths than roads.

Commerce. The central commercial area is currently occupied by an office building, with more offices, apartments, an inn, a deli/restaurant, and a dance/exercise studio to follow.

Community Focus. The village green and recreation center - with a large meeting and party room, kitchen, swimming pool and large playing field - provide the focus for socializing a gatherings. A preschool operates in the building during the week.

Area Devoted to Streets and Parking	Street Widths	Livable Higher Density (people per square mile)	Reducing Vehicle Miles (miles traveled per car)
Village Homes: 15% Vicinity: 22%	Village Homes: 23ft. Vicinity: 44ft.	Village Homes: 6,933 Vicinity: 3,458	Village Homes: 11,300 Vicinity: 13,400

Total Acres 60	Housing Units 240	Office Sq. Ft. 4,000	Agricultural 12,000 sq. ft.
Population 650	Avg. Density (units/net acre) 7.7	Avg. Walk to Village Center 4.3 minutes	Avg. Min. & Max. Temperature 39° - 95°

Urban Design and Stormwater Runoff

Stormwater runoff can be beneficially used to recharge groundwater systems and relieve pressure on expensive stormwater infrastructure. Often perceived as a problem in the past, due to the costs of controlling storm flows and pollutants, stormwater flows present an opportunity for groundwater recharge and other beneficial uses. Water managers are exploring new approaches to harvesting stormwater flows, and water quality regulations are increasingly requiring localized capture and treatment approaches. The National Water Sector Assessment notes that: [33]

> Many urban areas already have a problem with urban storm runoff that, when untreated, leads to problems with both inland and coastal water quality, which in turn has well documented direct effects on human health. Changes in climate conditions can affect the intensity of urban storm runoff, particularly in regions where precipitation increases.

Village Homes utilized and effective surface drainage approach at a *savings* of $800 per lot (in 1975 dollars). Rather than piping stormwater off site in the conventional approach, the developers utilized natural drainage systems. The following images indicate how the system works.

Water flows in surface channels through the site to ponding areas, where the water soaks in.

Surface drainage and recharge designs are a simple, cost-effective strategy to deal with stormwater flows. The climate models indicate the possibility of increased precipitation, and there is some indication that the intensity of precipitation events may increase. This type of coping strategy would build resilience in systems, improve groundwater recharge, and reduce damages due to high flows from impervious surfaces.

Two views of surface channels during rain events.

The site design includes swales and drainage channels to direct the water.

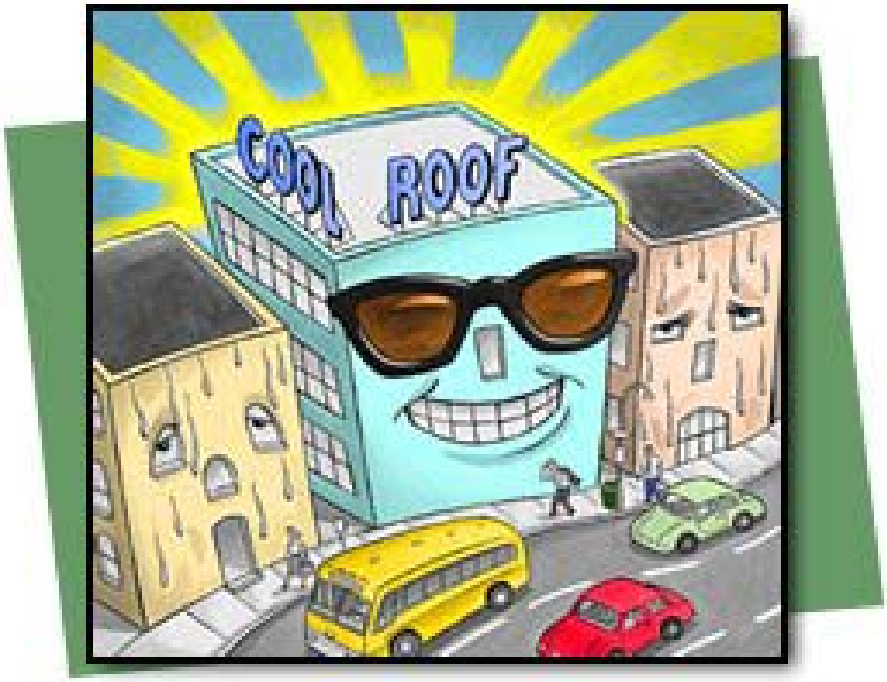
Reducing Urban Heat Island Impacts

Summer temperatures in urban areas are elevated by a "heat island" effect resulting from paved areas (hardscape) and buildings absorbing solar radiation. The result is an increase in energy use for air conditioning and increased ozone formation. During heat waves, heat islands exacerbate the extreme conditions.

Several strategies are available for reducing the heat island effect and thereby improve quality of life conditions and decrease both energy use and negative health impacts. These strategies include such simple measures as light roof colors, reducing paved areas, and planting appropriate trees and vegetation for shading. The results can be significant.

Art Rosenfeld et al. calculated that cool roofs and shade trees could reduce summer temperatures in Los Angeles by about six degrees F, which would in turn cut the air conditioning load (at peak time) by 20% and population-weighted smog by about 12%, saving $0.5 billion per year.[34]

The "Cool Roofs" program is an example of an incentive-based policy approach designed to assist in delivering multiple benefits through energy efficiency programs. Additional information on the program is available at the Local Government Commission's web site: http://www.lgc.org/techserve/coolroofs/index.html.



The "Cool Roofs" Program[35]

The Cool Savings Program provides rebate incentives to reduce the peak electricity demand from air conditioning systems resulting from solar energy absorbed by roof surfaces and rooftop ducts and transferred as heat into air-conditioned space.

What's a Cool Roof? Most traditional roof materials stay "hot", absorbing 70% or more of the solar energy striking them. Cool roofs absorb less than 35% of this solar energy staying 50 to 60° F cooler during peak summer conditions than traditional dark roof materials.

What are the Benefits of a Cool Roof? Because cool roof materials stay cooler, they offer many benefits to building owners and the community at large, including:

- Reduced peak electricity demand
- Reduced cooling energy use
- Improved building comfort
- Reduced building maintenance costs
- Reduced heat island effect
- Reduced air pollution
- Reduced roofing waste

The Local Government Commission site provides information on the program and links to other sites.

Green Building

Green building is a term and concept that covers a number of elements from improved energy efficiency to the use of specific building materials. Many of the practices included in green building are directly relevant to reducing the potential impacts of climate change. For example, buildings that remain comfortable under increased temperatures without requiring additional energy inputs provide various benefits including cost savings and improved comfort and productivity.

Alexis Karolides of Rocky Mountain Institute's Green Development Services provides the following description of *green building*: [36]

> The goal of green building is to analyze interconnected issues such as site and building design, energy and water efficiency, resource-efficient construction, lighting and mechanical design, and building ecology, and optimize all these aspects in an integrated design. Features that might have higher individual costs (e.g. better windows) may actually reduce the whole building cost because other elements such as the heating system can be downsized or eliminated. In order to

> capture these multiple benefits of synergistic design elements, the building must be evaluated as a whole, not "value-engineered" item by item.

Karolides notes that green building does not have to cost more up front. In fact, building green often costs less. "Careful *front-loaded* planning and design can pay for itself—with interest—in avoided downstream costs such as elaborate mechanical systems, expensive redesigns, drawn-out approvals, litigation, and stalled construction."

Here is how leading practitioners approach integration to achieve multiple benefits:[37]

> Green building experts encourage project teamwork to promote an open exchange of ideas and generate integrated, whole-systems solutions. In the conventional, linear development process, key people are often left out of decision-making or brought in too late to make a full contribution. Collaboration, on the other hand, can reduce and sometimes eliminate both capital and operating costs while at the same time meeting environmental and social goals. In addition, the process can anticipate and avoid technical difficulties that could add expense later in the process. It can also produce a "big picture" vision that goes beyond the original problem, permitting one solution to be lever-aged to create many more solutions—often at no additional cost.
>
> The U.S. Green Building Council's LEED (Leadership in Energy and Environmental Design) rating system for new and existing commercial, institutional, and high-rise residential buildings is a tool to evaluate environmental performance from a "whole building" perspective over a building's life cycle, providing a definitive standard for what constitutes a green building. The Council has asserted that a LEED silver-rated building should not cost more than a conventional building. (LEED Platinum does typically cost more because it may involve cutting edge technologies and levels of performance that are far above and beyond standard construction.)
>
> Many players in the real estate market are realizing that green development is good business. Developers, builders, and buyers are discovering that "green" enhances not only health and quality of life, but also the pocketbook.

Quantification of multiple benefits has been undertaken is various studies. Joe Romm (then at the U.S. Department of Energy) and William D. Browning at Rocky Mountain Institute provide some impressive numbers in a series of case studies included in a paper entitled: *Increasing Productivity Through Energy-Efficient Design: Greening the Building and the Bottom Line.*[38] Romm and Browning note that some of the most valuable benefits, in both direct economic metrics and in the contribution these buildings make to quality of life, are *on top of* the substantial energy savings. They point to benefits such as a 15% drop in absenteeism and a 15% increase in production as evidence of significant multiple benefits.

Increasing Productivity Through Energy-Efficient Design
Greening the Building and the Bottom Line[39]

Adapted from a Report Prepared by
Joseph J. Romm, U.S. Department of Energy, and
William D. Browning, Rocky Mountain Institute

Energy-efficient building and office design offers the possibility of significantly increased worker productivity. By improving lighting, heating, and cooling, workers can be made more comfortable and productive. An increase of 1 percent in productivity can provide savings to a company that exceed its entire energy bill. Efficient design practices are cost-effective just from their energy savings; the resulting productivity gains make them indispensable.

In their paper, Romm and Browning document eight cases in which efficient lighting, heating, and cooling have measurably increased worker productivity, decreased absenteeism, and/or improved the quality of work performed. They also show that efficient lighting can measurably increase work quality by reducing errors and manufacturing defects. The case studies presented include retrofits of existing buildings and the design of new facilities, and cover a variety of commercial and industrial settings. They include:

1. The main post office of Reno, Nevada, a lighting retrofit with a six-year payback that led to a 6-percent gain in productivity—worth more than the cost of the retrofit.
2. Boeing's "Green Lights" effort, which reduced its lighting electricity use by up to 90 percent, with a two-year payback (a 53-percent return on investment) and reduced defects.
3. Hyde Tools' implementation of a lighting retrofit with a one-year payback and an increase in product quality estimated to be worth $25,000 annually.
4. Pennsylvania Power & Light's upgrade of the lighting system in a drafting facility that produced energy savings of 69 percent and a 13-percent increase in productivity, with a 25-percent decrease in absenteeism.
5. Lockheed's engineering development and design facility, which saved nearly $500,000 a year on energy bills and gained 15 percent in productivity with a 15-percent drop in absenteeism.
6. West Bend Mutual Insurance's new building, which yielded a 40-percent reduction in energy consumption per square foot and a 16-percent increase in claim-processing productivity.
7. Wal-Mart's new prototype Eco-Mart, where enhanced daylighting through the use of skylights in one half of the store led to "significantly higher" sales than in the other half.
8. ING Bank's new headquarters, which used one-tenth the energy per square foot of its predecessor, created a positive new image for the bank, and lowered absenteeism by 15 percent.

Each case study identifies the design changes that were most responsible for increased productivity. While such gains may not necessarily be achievable by all companies, the cases profiled in the paper are by no means out of the ordinary. These companies realized significant productivity and energy savings because their former offices and plants were inefficient—but no more so than those of most American companies. As the eight case studies illustrate, energy-efficient design may be one of the least expensive ways for a business to improve the productivity of its workers and the quality of its product.

Clearly, there is a need for further research; however, the results of these few case studies indicate that the economic benefits of energy-efficient design may be significantly greater than just the energy cost savings. That energy efficiency provides numerous benefits has long been known. That it can lead to productivity gains far exceeding the energy savings gives it a new imperative. The results of these case studies are compelling, for two reasons. First, the measurements of productivity in most of the cases came from records that were already kept, not from a new study. Second, the gains in productivity were sustained and not just a temporary effect. Will just any energy retrofit produce gains in productivity? No, only those designs and actions that improve visual acuity and thermal comfort seem to result in these gains. This speaks directly to the need for good design, a total-quality approach that seeks to improve energy efficiency and improve the quality of workplaces by focusing on the end user—the employee. This is a point that seems to have been forgotten by many designers and building owners.

One of the eight studies is Lockheed's "Building 157." This project in Southern California provides an interesting example of the value, in both economic and quality of life terms, provided by intelligent design.

NEW BUILDING CASE STUDIES
LOCKHEED BUILDING 157 [40]

Cost:	*$2 million*
Measures:	*Daylighting, Energy Efficiency*
Energy Savings/Yr:	*$500,000*
Productivity:	*15% increase in production, absenteeism down 15%*

One of the most successful examples of daylighting in a large commercial office building is Lockheed's Building 157 in Sunnyvale, California. In 1979, Lockheed Missiles and Space Company commissioned the architectural firm, Leo A. Daly, to design a new 600,000-square-foot office building for 2,700 engineers and support people.

The architects posed a question to Lockheed: "If we could design a building for you that would use half as much energy as the one you're planning to build, would you be interested?" Lockheed said yes, and Daly's architects responded with a design for energy-conscious day-lighting that was completed in 1983.

Daly used 15-foot-high window walls with sloped ceilings to bring daylight deep into the building. "High windows were the secret to deep daylighting success," says the project architect, Lee Windheim. "The sloped ceiling directs additional daylight to the center of each floor and decreases the perception of crowded space in a very densely populated building."

Daylighting is also enhanced by a central atrium, or "litetrium," as the architects call it. The litetrium runs top to bottom and has a glazed roof. Workers consider it the building's most attractive feature. Other light-enhancing features include exterior "light shelves" on the south facade. These operate as sunshades or as reflectors for bouncing light onto the interior ceiling from the high summer sun; in the winter, when the sun's angle is lower, they diffuse reflected light and reduce glare.

The overall design separates ambient and task lighting, with daylight supplying most of the ambient lighting and task lighting fixtures supplementing each workstation. Continuously dimmable fluorescents with photocell sensors maintain a constant level of light automatically to save even more energy.

The open office layout and a large cafeteria were de-signed to foster interaction among the engineers. At the same time, workstations were tailored for employee needs. They included acoustic panels and chambers to block out ambient noise. When a worker moves forward into a chamber, the annoying sound of telephones becomes practically inaudible. Ambient noise was further controlled by sound-absorbing ceilings and speakers that introduced background white noise on each floor.

Employees love the building. More than a year after occupancy, a survey of workers at the building included the following representative responses. "My work space," says engineer Ben Kimura, "is 15 feet from the litetrium and the lighting is great. The office decor, arrangement, and temperature are ideal. There are many people working on this floor, but the feeling is not one of crowding, but of spaciousness. Inter-face with other departments is greatly facilitated because we're finally all in one building. By nature I'm very cynical, but the conditions in this building are far superior to any I've experienced in 30 years in the aerospace industry."

"I love my work space," says financial controller Joanne Navarini. "I think the building itself is very pretty; my own workstation is very functional. I am five workstations from the window and the light is fine. I use my task light and could order an additional desk lamp if I felt the need to. I like the daylight." Daylighting has saved Lockheed about 75 percent on its lighting bill. Since daylight generates less heat than office lights, the peak air-conditioning load has also been reduced. Overall, the building runs with about half of the energy costs of a typical building constructed at that time.

Daly's energy-efficient improvements added roughly $2 million to the $50 million cost of the building. The energy savings alone were worth nearly $500,000 a year. The improvements paid for themselves in a little over four years.

Perhaps more important, Russell Robinson, manger of Facility Interior Development, reported that productivity is up because absenteeism has declined. Lockheed itself has never published the figures concerning the improvements in absenteeism and productivity. But according to Don Aitken, then chairman of the Department of Environmental Studies at San Jose State, "Lockheed moved a known population of workers into the building and absenteeism dropped 15 percent." Aitken led numerous tours of Building 157 after it opened and was told by Lockheed officials that the reduced absenteeism paid 100 percent of the extra cost of the building in the first year.

The architect, Lee Windheim, also reports that Lockheed officials told him that productivity rose 15 percent on the first major contract done in the building com-pared to previous contracts done by those Lockheed engineers. Aitken reported something even more astonishing: Top Lockheed officials told him that they believe they won a very competitive $1.5 billion defense contract on the basis of their improved productivity—and that the profits from that contract paid for the entire building.

William S. Becker, of the U.S. Department of Energy, notes that green building makes good business sense in addition to providing environmental and health benefits.[41]

> In the not-too-distant future, all development will be green. Developers, builders and buyers will discover that green not only enhances their pocketbooks, but also their health and the quality of their lives. The developers who grasp this first will have an edge in a massive, emerging market.

The California Blueprint for Green Buildings

The California Sustainable Building Task Force released a report entitled *Building Better Buildings: A Blueprint for Sustainable State Facilities* in December of 2001.[42] It provides a 10-point comprehensive plan to implement the sustainable building goal "to transform California's state-owned buildings into state-of-the-art facilities designed to save precious environmental resources and taxpayer dollars."[43] Aileen Adams, Secretary of the State and Consumer Services Agency and chair of the Task Force, explained:[44]

> By definition, "sustainable" buildings use superior design and construction methods to integrate environmentally-sound technologies and practices, which improve energy efficiency, indoor air quality, and employee health, comfort, and productivity. This *Blueprint* provides a plan to ensure that state buildings and policies incorporate practices

> that are good for the environment, fiscally responsible, and promote workplace health and productivity. As a result, state facilities will operate more efficiently, but also will save taxpayer dollars during the life of those facilities while providing more productive places to work and learn.

The State and Consumer Services Agency Task Force notes that:[45]

> By incorporating sustainable building practices into the capital outlay process, state government can have a positive impact on the environment, as well as building-design and construction practices. The State of California owns and operates nearly 190 million square feet of building space and leases an additional 21 million square feet of office space. The state invests more than $2.5 billion annually in the design, construction, and renovation of its facilities. According to the State of California's Five-Year Capital Outlay Plan, anticipated infrastructure needs during the next 10 years exceed $82 billion, including new schools, office buildings, infrastructure projects, renovations, and other bond-funded construction activities.

The *Blueprint* includes the following sustainable building strategies:

- Modifying the state's capital outlay policies and process to incorporate sustainable building goals;
- Incorporating integrated design, life cycle costing, building commissioning, and post occupancy evaluation processes into the state's capital outlay program;
- Developing cost-effective building performance standards to measure the effectiveness of sustainable building practices;
- Establishing a systematic reporting and review process to ensure that state building performance improves continuously;
- Developing exemplary projects and model sustainable buildings that demonstrate the effectiveness of sustainable building and operating processes; and
- Assisting state agencies in the development of sustainable building projects.

The state is implementing green building elements in new construction, including a new complex of buildings several blocks from the state capitol.

> The most prominent example of the state's sustainable building implementation efforts is the Department of General Services' Capitol Area East End Complex, a $392 million, five-building project. The largest state government office building construction project in California's history, this 1.5 million square-foot complex incorporates various sustainable building features, including recycled-content materials, raised floor ventilation, and highly efficient plumbing and irrigation systems. These buildings are expected to exceed existing state energy efficiency standards by more than 30 percent, saving taxpayers roughly $400,000 annually in energy costs alone.

Land-Use Planning in Specific Regions

Coastal Land-Use Planning

The Coastal Land Use work group at the California regional workshop provides the following response strategies:[46]

> The term "coastal land use" should be considered broadly to include not only the terrestrial coastal zone, but also, offshore islands, upland watersheds, littoral zones, marine ecosystems, and established marine refuges. Responses to impacts and stresses from global climate changes are considered in two contexts: the built environment and the natural environment.
>
> For impacts to the natural environments (e.g.: water temperature warming and species changes, flooding and freshwater impacts, wetland inundation, beach bluff erosion) we would strive to enable nature to take its course, with natural adaptation, new equilibrium conditions, etc. being re-established over time. We should intensively study and research such ecological phenomena; and strive to avoid interfering with such processes (such as premature harvesting of emerging fishery stocks).
>
> For impacts to the built environment (houses, roads, ports, airports, delta levees) we should establish strategies priorities such as:
>
> - Defend with engineered fortifications assets of high strategic value such as airports, ports, delta levees (for water supply security).
> - Relocate (or engineer alternative solutions) vital assets to higher ground.
> - For less strategic aspects of the built environment (housing on coastal bluffs), simply retreat and let nature take its course.
>
> For new development of any kind, authorize the Coastal Commission (or local government) to consider "risk-of-harm" from impacts of global climate change. After due consideration of risk-of-harm, developments may be approved only with:
>
> - No assured warranty of safety of loss
> - Private insurance to underwrite the risk
> - Self-insurance to bear any costs or losses
>
> Full disclosure of potential risk (i.e.: coastal erosion, beach houses, earthquake, slope stability, fire danger, flooding, etc.) should be used to inform the due diligence process. After disclosure, the risk/liability shift from the public sector to the private sector. Thereafter, any development in the coastal area would be tempered by incorporation of risk and cost calculus.

The group also noted that: "New institutions are not needed. Indeed, the Coastal Commission and local governments are the appropriate bodies for planning and decision-making."

Planning in Fire-Prone Regions

The California Department of Forestry and Fire Protection and the USDA Forest Service conduct land cover mapping and monitoring to enhance fire protection and natural resource management on public and private lands in California. (This program uses Landsat Thematic Mapper (TM) satellite imagery to map land cover types and derive land cover changes across all ownerships.) Information is available at California Department of Forestry and Fire Protection, http://www.frap.cdf.ca.gov/projects/land_cover/index.html

Fire-prevention methods include clearing brush away from buildings, mapping fire behavior and identifying areas of high fire hazard where development should be limited, changing building codes to increase the fire resistance of roofing, improving access for emergency and evacuation vehicles, and increasing public education and information.[47] These measures make a great deal of sense both as a way of dealing with current stresses and as a hedge against future climate changes.

Wildland Fire Safety Regulations[48]

In 1986, the California Board of Forestry, supported by CDF, introduced legislation (SB 1075, Rogers) to develop minimum statewide standards for defensible space in State Responsibility Areas (SRA). This legislation was motivated by the general lack of response by local government to the wildland fire protection problem over the previous 20 years. This comprehensive wildland fire safety legislation was passed by the legislature and signed by the Governor in 1987. SB1075 required the California Board of Forestry to establish minimum fire safety requirements that applied to SRA. These requirements cover emergency access and water supplies, addressing and street signing, and fuel modification relating to new construction and development.

Response Strategies for Water

Only through enlightened public understanding of these complex issues can we hope to integrate divergent viewpoints and contending interests into a wise policy of water management which will have sufficient resiliency to cope with climatic change and other developments in our society…"

William L. Kahrl, *The California Water Atlas*[49]

Building Resilience in Water Systems

William Kahrl's observation is echoed in discussions throughout California. "Enlightened public understanding" of these complex issues is indeed key to building resilience in systems and to effective coping and adaptation strategies to deal with climate change. The focus of this section is on building that "sufficient resiliency" through policy and management to deal with climate change.

Many strategies are available to cope with and adapt to the potential impacts of climate change and variability on water systems in California. Some involve non-structural approaches such as water pricing and management practices, while others involve structural approaches. Discussions are already occurring regarding the relative merits of the two approaches.

The purpose of this assessment is to inform the discussion. At this point in time, the computer models described above generally do not provide specific information regarding future conditions in specific locations in California. They do provide useful information regarding potential changes and impacts such as probable changes in snowmelt patterns. While average warming is fairly certain, it is not clear whether it will be wetter or drier in Southern California, for example, or whether precipitation patterns will shift seasonally. Therefore, it makes sense to first consider a range of options that build resilience through cost-effective "no regrets" strategies under conditions of uncertainty.

Addressing Multiple Stresses

Climate change and variability is just one of a number of factors putting pressure on water systems in California. As noted, rapid population growth, land-use changes, contamination of surface and ground water resources, and the need for ecosystem protection and restoration are all occurring simultaneously. The water sector report lists the following tools water agencies and managers are exploring:[50]

1. incentives for conserving and protecting supplies,
2. opportunities for transferring water among competing uses in response to changing supply and demand conditions,
3. economic changes in how water is managed within and among basins,
4. evaluating how "re-operating" existing infrastructure can help address possible changes, and
5. new technology to reduce the intensity of water use to meet specific goals.

Many of these approaches are already being used in California with good results. An indication of the potential for efficiency improvements, or example, is provided by the City of Los Angeles. The Los Angeles Department of Water and Power (LADWP) notes that "despite a population increase of slightly over 35% (or nearly one million people) since 1970, current water use has grown by only 7%, and per capita usage has been *reduced by 15%*."[51] Industries, farms, and communities throughout the state are making similarly important strides in water use efficiency.[52] This section reviews some of the economic and technical issues relating to water management and suggest coping and adaptation strategies.

A useful starting point for the discussion of response strategies to climate change is a recognition that even absent any change in climate, California can expect both wet and dry conditions. The science reviewed above indicates that we may well see wetter wets and drier drys. In either event, or both, the stakeholders and experts involved in the California assessment agree that response strategies that build *resilience* and the capacity to deal with variability will be helpful.

Design Systems for Flexibility

Response strategies should be designed to tap management and institutional options that allow for flexibility. The water sector report made specific note of the IPCC conclusion that "water demand management and institutional adaptation are the primary components for increasing system flexibility to meet uncertainties of climate change."[53] This is another important feature of the *no regrets* approach. Locking in large, long-term capital investments under conditions of uncertainty is a risky strategy. Whenever possible, flexibility is desirable as a management strategy.

Plan and Invest for Multiple Benefits

An example is the water supply, energy, wastewater, and environmental benefits that accrue from water use efficiency improvements.

Water managers often do not receive credit in the cost/benefit analysis, or otherwise, for providing these multiple benefits. For example, total energy savings for reducing marginal (e.g. imported) supplies of water in Southern California are estimated at about 3,500 kWh/acre-foot.[54] Conveyance over long distances and over mountain ranges accounts for the high energy intensity. This is an *average* figure for marginal supplies for the region. In some geographic areas, the figure is *higher* due to additional pumping requirements. In addition to avoiding the energy and other costs of pumping additional water supplies, there are environmental benefits through reduced extractions from stressed ecosystems such as the delta.

Water Policy, Planning, and Management

Roger Revelle and Paul Waggoner concluded in a 1990 American Association for the Advancement of Science (AAAS) study on the potential implications of global climate change for the water resources of the United States:[55]

> Among the climatic changes that governments and other public bodies are likely to encounter are rising temperatures, increasing evapotranspiration, earlier melting of snowpacks, new seasonal cycles of runoff, altered frequency of extreme events, and rising sea level... *Governments at all levels should reevaluate legal, technical, and economic procedures for managing water resources in the light of climate changes that are highly likely*.

The AAAS panel recommended:[56]

> During planning, managers should be alert for economical measures to increase flexibility and accommodate climatic variability, sea-level rise, and as we learn more about it, climatic change. They should exploit opportunities to retain or increase flexibility of systems, especially since such measures may be fairly inexpensive if put in an original design.

The Second World Climate Conference concluded similarly in 1991 that:[57]

> The design of many costly structures to store and convey water, from large dams to small drainage facilities, is based on analyses of past records of climatic and hydrologic parameters. Some of these structures are designed to last 50 to 100 years or even longer. *Records of past climate and hydrological conditions may no longer be a reliable guide to the future. The design and management of both*

structural and non-structural water resource systems should allow for the possible effects of climate change.

In 1997 the AWWA, the largest professional association of water utilities and providers in the United States, published a set of recommendations from its Public Advisory Forum. Among the recommendations to water managers were the following:

American Water Works Association
Public Advisory Forum Recommendations[58]

While water management systems are often flexible, adaptation to new hydrologic conditions may come at substantial economic costs. Water agencies should begin now to re-examine engineering design assumptions, operating rules, system optimization, and contingency planning for existing and planned water-management systems under a wider range of climate conditions than traditionally used.

Water agencies and providers should explore the vulnerability of both structural and non-structural water systems to plausible future climate change, not just past climate variability.

Governments at all levels should re-evaluate legal, technical, and economic approaches for managing water resources in the light of possible climate change.

Cooperation of water agencies with the leading scientific organizations can facilitate the exchange of information on the state-of-the-art thinking about climate change and impacts on water resources.

The timely flow of information from the scientific global change community to the public and the water-management community would be valuable. Such lines of communication need to be developed and expanded.

The Water Sector report concludes that: "Prudent planning requires that a strong national climate and water research program be maintained, that decisions about future water planning and management be flexible, and that the risks and benefits of climate change be incorporated into all long-term water planning. *Rigid, expensive, and irreversible actions in climate-sensitive areas can increase vulnerability and long-term costs*."[59] The report made the following recommendations regarding coping and adaptation:

Coping and Adaptation[60]

There are many opportunities to reduce the risks of climate variability and change for U.S. water resources. Tools for reducing these risks have traditionally included supply-side options such as new dams, reservoirs, and pipelines, and more recently, demand-management options, such as improving efficiency, modifying demand, altering water-use processes, and changing land-use patterns in floodplains.

We make the following observations and recommendations:

- Prudent planning requires that a strong national climate and water monitoring and research program should be maintained, that decisions about future water planning and management be flexible, and that expensive and irreversible actions be avoided in climate-sensitive areas.
- Better methods of planning under climate uncertainty should be developed and applied.
- Governments at all levels should re-evaluate legal, technical, and economic approaches for managing water resources in the light of potential climate changes.
- Improvements in the efficiency of end uses and the intentional management of water demands must now be considered major tools for meeting future water needs, particularly in water-scarce regions where extensive infrastructure already exists.
- Water managers should begin a systematic reexamination of engineering designs, operating rules, contingency plans, and water allocation policies under a wider range of climate conditions and extremes than has been used traditionally.
- Cooperation between water agencies and leading scientific organizations can facilitate the exchange of information on the state-of-the-art thinking about climate change and impacts on water resources.
- The timely flows of information among the scientific global change community, the public, and the water-management community are valuable.
- Traditional and alternative forms of new supply, already being considered by many water districts, can play a role in addressing changes in both demands and supplies caused by climate changes and variability. Options to be considered include wastewater reclamation and reuse, water marketing and transfers, and even limited desalination where less costly alternatives are not available and where water prices are high.
- Prices and markets are increasingly important for balancing supply and demand. Because new construction and new concrete projects can be expensive, environmentally damaging, and politically controversial, the proper application of economics and water management can provide incentives to use less and produce more.
- Even without climate change, efforts are needed to update and improve legal tools for managing and allocating water resources. Water is managed in different ways in different places around the country, leading to complex and often conflicting water laws.

Economics and Water

> *Prices and markets are increasingly important tools for balancing supply and demand for water and hence for coping with climate-induced changes.*
>
> Water Sector Assessment Team[61]

There are costs and benefits to both changes and responses to change. Thoughtful consideration of options strategies to implement them will improve our ability to cope and adapt to climate change. As the water sector report notes:

> All of the physical and ecological impacts of climate change will entail social and economic costs and benefits. … The costs of water supply and protection from floods and droughts have been rising for much of this century and they are likely to continue rising even in the absence of climate change. Future water costs will depend on the costs of developing new supplies, implementing conservation options, foregoing desired water uses, meeting water quality standards, and protecting natural aquatic ecosystems. Additional factors likely to contribute to higher future costs of water are the threats to existing supplies posed by contamination and groundwater depletion.[62]

Understanding Water Needs and Demand

Coping and adaptation strategies are based in part on our understanding of future needs. In the case of water policy, actual "demand" for water in the future is a function of price. The Southwest Regional Climate Assessment made an important observation regarding the role of demand estimates and economic analysis that is equally relevant for the California region. Noting that the "demand" projections used for water planning are based on incomplete, and at time flawed, analyses the team notes that:

> Coping mechanisms based on current studies may not result in desired outcomes and may have unintended welfare effects on some consumer groups. Therefore, research to improve the accuracy of demand studies is the necessary first step in managing the scarce water resources of the Southwest and coping with any consequences of climate variability and change. [63]

Environmental organizations have argued that economics be taken seriously. Noting that core economic principles and analysis have not been adequately integrated into its water supply reliability planning, a number of leading organizations in California made the following recommendation:

> Past water pricing policies have consistently understated the "true cost" of water development through financial subsidies and by failing to assign economic cost to ecosystem destruction. These policies have combined to inflate expectations, create a perception of shortages and encourage environmentally damaging water development.
>
> Recognize that the price of water has an effect on both the demand for water and the supply of water. As the cost of developing additional water supplies increases, demand for water will decrease and other sources of water (e.g. transfers and conservation) will become even more competitive.[64]

The Role of Markets and Economics

An important distinction needs to be made at the outset of this discussion of economics, markets, and policy applications. The use of market-based policy approaches does *not* equal, or imply, privatization of water systems or water marketing. Market-based tools, such as increasing block-rate pricing structures, utilize basic economic principles as they apply to scarce resources. Pricing structures, rebates for implementation of efficiency measures, and other policy and management tools utilize market principles to achieve policy goals such as improved efficiency and reliability. Water marketing and issues relating to privatization are separate. That is, market-based tools may be applied in either public or private water management. It is possible to employ market-based tools in publicly owned and operated water systems, and indeed, some of these tools are commonly employed throughout the state. The water sector report notes:

> Because new construction and new concrete projects are increasingly expensive, environmentally damaging, and socially controversial, new tools such as the reduction or elimination of subsidies, sophisticated pricing mechanisms, and smart markets provide incentives to use less water, produce more with existing resources, and reallocate water among different users.[65]

Water marketing and privatization of the resource raise important political concerns and questions. This has been especially the case following the less-than-successful policy adventures in the electrical energy sector in California. It is therefore important that the discussion of markets and market tools delineate the two issues. The following discussion seeks to clarify the elements, and differences, between the terms and concepts.

Pricing, Demand Elasticity, and Supply "Shortages"

> *Economists and others are beginning to advocate an end to the treatment of water as a free good.*
>
> Report of the Water Sector Assessment Team [66]

Water, like all goods allocated in market systems, is priced in some way. Water *use* is in turn influenced by price along with other factors. When the price is set at below-market or below-cost levels, users will tend to consume more than they would if the price reflected full costs or market prices. This bit of arcane economics is important because *use* will tend to be greater when resources are under-priced. "Shortages" that result are in fact "longages" of demand for resources that are undervalued. This is because users tend to *under-invest* in efficiency and *over-use* resources when they are under-valued. We call this a "shortage" because users want more *at that price level* than is available. When the price is increased, users' "demand" shifts downward. In a market that is allowed to "clear" there will be no shortage. California will *always have a shortage* of high-quality water priced below market value.

Economists argue that demand for goods is inversely related to price. That is, as the price of a good increases, the quantity demanded decreases. In the classic supply and demand curves, demand moves along the curve in response to price. (The curve *shifts* if other factors such as substitutable goods are available.) Response to price is called *elasticity*. This response, or elasticity, is typically represented as a ratio of the percentage change in the quantity of a good demanded over the percentage change in the price for a unit of the good. A value greater than one is elastic, whereas a value of less than one is inelastic. Or, in plain English, when people respond to price signals and use less of a good when prices go up, there is demand elasticity.[67]

Demand elasticity is a critically important issue for water policy. If price matters, it can be used as a policy and management tool. If it does not, policies designed to use price mechanisms will fail to have the desired results. It seems logical that consumers would use less of a good as it gets more expensive, but the empirical studies yield varied results.[68]

> From a policy perspective, an accurate elasticity estimate is important for two reasons. First, how will consumers respond to price changes? Second, given consumer response to a price change, what happens to total revenue? For an inelastic good, total revenue increases (decreases) if price increases (decreases). For an elastic good, total revenue increases (decreases) as price decreases (increases). While consumer response is important in designing effective policies to meet water consumption goals, understanding the impact on total revenue is important to the water provider who has traditionally tried to meet its delivery costs in the pricing structure.[69]

In California, rates are used as management tools in many water service areas. Increasing block rate structures are used in which consumers pay a "lifeline" rate for a specified amount of water.

A second tier, or block, increases in price, followed by additional increments. Hewitt and Hanemann found a strong response to block rate structures in California applications, suggesting that price is a useful policy tool.[70]

Water Transfers, Banking, and Marketing

There are linkages between water transfers, marketing, and banking, but they are not synonymous. The terms represent different activities that need to understood individually, even though they are often linked and overlapping in practice. Water *transfers* can and do occur without water *markets*. Water *banks* may facilitate both transfers and marketing, but they can also function independent of them. Water *markets* do not necessarily imply interbasin transfers. Each of the terms and concepts are outlined below.[71]

Water Transfers

Water transfers have been taking place between hydrologic basins, or watersheds, for a century and a half in California. Water from one region is conveyed to others for various purposes. For example, water flowing into the Owens Valley from the Eastern Sierra was transferred to the Los Angeles basin in an early and infamous example of inter-basin transfers. San Francisco, the East Bay Municipal Utility District, and others tapped water from the west slopes of the Sierra to supply distant urban areas. In the mid-1900s, both the federal and state water projects tapped water in Northern California and transferred it to areas south of the delta. MWD tapped the Colorado River for use in Southern California. Many smaller-scale transfers have occurred throughout the state.

There are various sources of water that can be transferred. Each is constrained by various legal, regulatory, market, and physical parameters. A California Legislative Analyst's Office (LAO) report identifies the following:

Sources of Water for Transfers

- Land fallowing and crop shifts to less water-intensive crops.
- Water recycling, such as recycling water from wastewater treatment plants for industrial and irrigation purposes.
- Groundwater pumping instead of using surface water rights, thereby freeing up surface water for transfer.
- Storing excess surface water from wet years in underground aquifers to be later pumped when surface supplies are low.
- Water conservation, in both the agricultural and urban sectors. For example, this includes farmers using water-saving irrigation technologies and homes and businesses using water-efficient landscaping and bathroom fixtures.
- Withdrawals from surface storage supplies that were not otherwise planned to be made.

Transfers do not create new water, they simply reallocate it. The LAO report notes:[72]

> Water transfers in and of themselves do not generate new sources of water. Rather, water transfers are a mechanism to *reallocate* water among water users, thereby making water more widely available for use on a statewide basis.

Recent legislation has encouraged water transfers. In the 1980s and 1990s, the legislature was active in encouraging and facilitating water transfers.[73] Until 1980 there was some uncertainty regarding water transfers and whether transferred rights were protected as reasonable and beneficial. The California Constitution requires reasonable and beneficial use of the state's water.[74] Following recommendations of the Governor's Commission on Water Rights in (1976), the legislature established policy in 1980 that explicitly facilitates water transfers and declares that they do not constitute unreasonable or wasteful use.[75] Two years later the legislature *required* the Department of Water Resources and other agencies to facilitate and encourage transfers,[76] and it authorized local water districts to transfer surplus water to users located outside of their districts.[77] In 1986, the legislature went further still and mandate that DWR create a program to facilitate voluntary transfers by providing a list of entities interested in transferring water.[78] It also prohibited the department and local agencies from denying access to unused capacity in conveyance systems to parties interested in transferring water through them.[79] A SWRCB report on transfers summarizes the state's policy with a simple rule:[80]

> You can transfer water if it is your water and not somebody else's water, provided the transfer does not injure another water right holder or unreasonably affect instream beneficial uses.

The LAO found "general agreement that existing state law on water transfers does not reflect a clear and consistent policy." They also found agreement that "the state does not have a comprehensive database of information on transfers that are taking place and on the impact of these transfers. According to stakeholders, the lack of a clear statutory policy and comprehensive database impedes transfers and undermines third-party protection.[81]

A government website has been created to support water transfers. A cooperative effort between state and federal agencies, the web site is "an online water market information source developed as part of the CALFED Bay-Delta Program." It is designed "to supply potential water transaction participants, affected third parties, and other interested parties with information to assist the efficient transfer of water."[82]

Water Banks

Water "banks" function as repositories into which deposits are made, presumably when water is abundant, and out of which withdrawals are made when water is needed. Water banks are an important element of transfers and markets. Both transfers and markets are possible without them, but the ability to store water when it is abundant and withdraw it when it demand is high created value.

Drought Water Bank Summary[83]

Year	Source of Drought Water Bank Water (taf)					Amount Allocated[a] (taf)
	Purchase Price($/af)	Surplus Reservoir Storage	Groundwater Substitution	Fallowing	Total Sources	
1991	125	147	259	415	821	390
1992	50	32	161	0	193	159
1994	50	33	189	0	222	174

[a] Amount allocated for urban, agricultural, and environmental uses. This represents the actual supply developed by the bank after conveyance and fish and wildlife requirements were met.

DWR is becoming a full-service banker. It provided banking services in 2001 and has set up arrangements for 2002. The department "implemented a 2001 Dry Year Water Purchase Program, which secured 138,800 acre-feet of water from willing sellers in Northern California and provided it to eight water agencies to help offset their water shortage conditions." The 2002 program "allows agencies that entered the program by November 30, 2001 to request DWR to obtain options for water that would be exercisable by March 2002 if the year is dry. The Program also will allow agencies that sign up and pay deposits prior to the end of March 2002 to participate in direct purchases of water provided by willing sellers and brokered through DWR. The program is intended to reduce the possibility of adverse economic impacts and hardship associated with water shortages, and is open to all water agencies."[84] Prospective purchasers are invited to review the Memorandum of Understanding for the Program on the web[85] and are asked to indicate how much water they have available, their interest in selling options on the water to DWR, the water source, their asking price per acre-foot, and the address and phone number of the contact at their agency.

Water Markets

Markets are characterized by, among other features, open access to buyers and sellers. A true market for water does not exist in California, and there are concerns regarding the advisability of creating such a market. Nevertheless, market-based transactions and activities are occurring, supported by policy, and they are providing important lessons. So far it has been a turbulent experience for many of the participants. It is difficult, and perhaps of no particular value, to delineate precisely where transfers become markets. This discussion seeks to frame the issues without focusing on a precise line separating the two terms.

Following the increasingly enthusiastic support for water transfers in California in the 1980s, the federal government moved into the arena with important legislation in the early 1990s. Congress passed the *Central Valley Project Improvement Act* (CVPIA) in 1992 with explicit provisions that were designed to both facilitate and encourage water markets and water transfers.[86] The federal legislation authorized the use of federal facilities and the transfer of federal water in the expanding market activities. CVP water can now be sold, for a profit, either within or outside the boundaries of the CVP service area.

CALFED, a cooperative policy effort between state and federal agencies, formally endorsed water transfers and marketing in its Record of Decision (ROD) in 2000.[87] The water transfer program in the ROD provides that the agencies will:

> Encourage the development of a more effective water transfer market that facilitates water transfers and streamlines the approval process while protecting water rights, environmental conditions, and local economic interests.

As part of its support, CALFED established a web site called "On Tap" to: "provide information on historical water transactions and provide an online resource to people involved in water markets in California."[88] CALFED explains its role as follows:[89]

> CALFED recognized that an effective water market is one of several water management tools needed to improve the reliability of the State's water supply. CALFED also recognized that a functioning water market already exists. The existing market has raised concerns regarding adverse impacts to other users, rural economies, and the environment. Past water transactions have highlighted inconsistent interpretations of State water law, the need for reliable conveyance access for cross-Delta transfers, and a need to simplify the complex approval process.

The U.S. National Assessment water sector team provided the following observation regarding water marketing:

> The characteristics of water resources and the institutions established to control them have inhibited large-scale water marketing to date. Water remains under-priced and market transfers are constrained by institutional and legal issues. Efficient markets require that buyers and sellers bear the full costs and benefits of transfers. However, when water is transferred, third parties are likely to be affected. Where such externalities are ignored, the market transfers not only water, but also other benefits that water provides from a non-consenting third party to the parties to the transfer. [90]

Water System Costs, Policy Planning, and Economic Models

Jay Lund and Richard Howitt of UC Davis have undertaken a major modeling effort (CALVIN) that seeks to link physical factors (hydrology) with economics factors for both the state and federal water projects in the Central Valley.[91] The project is funded by both the California Resources Agency and CALFED. Lund and Howitt explain the effort as follows:

> Water is scarce in California, and better options and frameworks are needed for water management. This project provides the foundation for a different approach to water management in California, combining powerful ideas from economics and engineering optimization with advances in software and data to suggest more integrated management of water supplies regionally and throughout California. While these newer ideas and methods cannot by themselves "solve" California's water problems, they can help us move beyond approaches that might have been more appropriate in the past and they illustrate what is possible and economically desirable for water management. There are better ways to think about solving California's water problems.[92]

This modeling project is the first large-scale effort to model both hydrology and economic factors in California. It is an ambitious undertaking, and it is constrained by both the hydrology models it uses and the lack of information on economic factors. Nevertheless, it is an important step forward.

If price does matter, and if it can be used as a management tool, what are the ways in which price signals and other market tools can be used? The next section examines the logic and role of market-based tools.

Using Market Tools

Water policy is profoundly affected by economic factors, even if there is no explicit recognition of the fact. For most of the 1900s, economics in water policy was restricted to analysis of the capital costs of new supply projects and the justification of expenditures of public funds. The perpetual "shortage" that California has been trying to "correct" in this way for decades is an elusive policy goal. Economists argue that the "gap" created by under-priced scarce resources will never be filled because people will always want more than can be supplied. California water history validates the economists' argument.

A better understanding of opportunity costs and the elasticity of demand, coupled to ever-improving models of demand and supply in the context of hydrology, may yield important guidance for policy. There is considerable work that needs to be done on both the hydrologic models and the economic models.

A number of market tools are available to support water management and policy objectives. Research indicates that these tools can be effective if water prices are within a range that is of concern to consumers. A judicious coupling of regulatory policy and market-based tools, employing each where they work best, holds considerable promise for more effective water management in California.

Demand Management, Conservation, and Efficiency

Water conservation professionals have only just begun to tap available efficiencies.

Richard Pinkham, Rocky Mountain Institute[93]

Leading water management agencies and sophisticated water users in the commercial and industrial, institutional, residential, and agricultural sectors are securing dramatically improved water-use efficiency gains and increased end-use services with less water through improved management approaches and various technology applications.[94] The water sector assessment notes that "evidence is accumulating that such improvements can be made more quickly and more economically, with fewer environmental and ecological impacts, than further investments in new supplies."[95]

Demand for water in California has generally been met through the diversion of surface water by groundwater sources. As technological capabilities developed and financing was made available, diversions and groundwater extraction increased in volume, scope, and geographic area. Interbasin and interstate transfers supplement water available within natural hydrological basins. Facilitated by technology and capital, agricultural and urban uses of arid lands was made possible in areas which otherwise would not have supported the activities.

Technologies of various kinds provide society with the means to use water in different ways. The focus of technology development has until recently been on the supply-side of the water equation. That is, the emphasis has been on extracting, storing, and conveying water from natural water systems to urban and agricultural users. Water *policy* in California and the West has generally been one of facilitating the use of technologies.

Technology: New Capabilities in Efficiency

Technology is applied to both the task of securing supplies of water and to the actual services provided by water. During the past century the United States has developed the most extensive and sophisticated water impoundment and conveyance system in the world. California maintains the largest and most diversified system of any state. This technological accomplishment, facilitated and managed by local agencies and the DWR at the state level, and the Bureau of Reclamation and Army Corps of Engineers at the federal level, is a credit to engineering capabilities and expertise. With this infrastructure in place, the agencies are now focusing on more efficient delivery and use of the resource.

Innovation and development of technology in the areas of end-use water applications progressed rapidly in the 1980s. Techniques and technologies ranging from laser leveling of fields and drip irrigation systems to the design of toilets and showerheads to new filter systems and treatment technology for cooling towers have changed the demand side of the equation. End-use applications of water now require much less volume than before to provide equivalent or

superior services, and implementation of the new technologies often provide immediate economic savings.

As mentioned above, the impetus for technological development and innovation in efficient use has been provided by the price mechanism and by policy. As water becomes more expensive, and as legal requirements prohibit waste, technology has provided a wide range of options for expanding the utility value of given amounts of water. Broader application of these technologies and techniques will yield significant "new supplies".

Efficiency improvements are now considered supply options, to the extent that permanent improvements in the demand-side infrastructure, including conveyance, provides reliable water for other uses including in-stream flow and consumption. Technology is also being applied to the problems of poisoning and contamination which past practices have created.

Richard Pinkham of the Rocky Mountain Institute provides an example of multiple benefits as follows:

Multiple Benefits of Water Efficiency[96]

Wringing more work from each drop of water sustains vital water supplies, lowers water bills, reduces the need for wastewater treatment, protects the environment, and creates wealth. Everybody wins:

Consumers. Installing water-efficient faucets, showerheads, toilets, and other devices can substantially reduce household water and sewage bills, and it can save even more money on energy for heating water. The use of these devices may also reduce or eliminate such problems as an overflowing septic tank. And don't overlook the comfort factor—an efficient showerhead lets twice as many people use the shower before the hot water runs out!

Communities. Some communities are physically short of water, or at least of uncontaminated water; some must pay expensive pumping costs; and many are seeking ways to avoid paying enormous capital costs to increase water storage or wastewater treatment capacity. Local budgets can be stretched only so far. A community that avoids building a larger water or wastewater facility will have more money for other services.

Utilities. Increasing water efficiency can enable utilities to reduce base-load and peak demand, making it possible to postpone or avoid tapping new supplies, expanding storage, or expanding treatment facilities. Programs that promote efficiency can enable a utility to achieve more predictable patterns of demand and buy time for effective long-term planning. For these reasons, many utilities offer rebate programs that enable customers to install efficient fixtures at a reduced price or for free, thus saving consumers even more money.

Companies. Using water more efficiently can reduce operating costs, often including fuel, chemicals, and labor.

The environment. Water not consumed can save a river from a dam and a wetland from destruction. Water not heated with fossil fuel means oil or gas not depleted, coal not burned, carbon not released to cause global warming, and sulfur not deposited as acid rain.

The economy. Money not spent on wasted water and energy is used more productively to create jobs and strengthen local businesses.

The measures listed in the California Urban Best Management Practices (BMPs) provide a specific example of cost-effective, technically viable options that are being successfully implemented around the state.[97]

California Urban Water Conservation Council
Urban Best Management Practices[98]

1. Water Survey Programs For Single-Family Residential and Multi-Family Residential Customers
2. Residential Plumbing Retrofit
3. System Water Audits, Leak Detection And Repair
4. Metering With Commodity Rates For All New and Retrofit of Existing Connections
5. Large Landscape Conservation Programs And Incentives
6. High-Efficiency Washing Machine Rebate Programs
7. Public Information Programs
8. School Education Programs
9. Conservation Programs For Commercial, Industrial, and Institutional Accounts
10. Wholesale Agency Assistance Programs
11. Conservation Pricing
12. Conservation Coordinator
13. Water Waste Prohibition
14. Residential ULFTs Replacement Programs

Energy, water supply, wastewater reduction, air quality, and environmental benefits accrue from the implementation of many of these measures.

Stormwater Management Strategies

Managing stormwater to reduce runoff and flood damage, reduce pollution, and improve water supply availability and quality is a policy goal in California. Recent efforts and policy measures aim to improve stormwater management. Climate change may bring additional challenges for those responsible for managing stormwater. This short review of design and retrofit options provides a set of alternative worth consideration.

Applications of stormwater strategies are site dependent. The following examples are provided for illustrative purposes. Local soil conditions, permeability, and other factors must be examined for each specific application.

Impervious surfaces such as roofs, roads and parking lots increase runoff during storm events. The first "flush" often collects and concentrates contaminants from those surfaces such as oils and sediment.

Various design approaches are available to direct stormwater runoff to landscaped areas where the water can percolate into the soil. In many cases, such as the Village Homes example presented earlier, groundwater recharge is one of the benefits derived from this approach.

Courtesy of Portland Bureau of Environmental Services

Courtesy of Bruce Ferguson

Courtesy of Low Impact Development Center

In each of these examples, water is directed to landscaped areas where runoff is intercepted. The designs include sloping of both the paved areas and the landscaped areas to follow normal drainage patterns.
This is an example of a parking lot retrofit. Water is first directed into a landscaped area. When flows exceed the capacity of the soils, water flows into the storm drain. By diverting a portion of the first flows the design reduces demands on the storm drain system.

Courtesy of Low Impact Development Center

Swales, like the one pictured below, capture down-slope flows and direct them along contours. This slows the rate of runoff and allows for recharge.

Courtesy of Portland Bureau of Environmental Services

"Daylighting" strategies involve restoring surface flows where underground pipes currently exist. These two examples of before and after daylighting are from Zurich. Examples in California include creeks on the University of California, Berkeley campus and many other sites.

Courtesy, City of Zürich

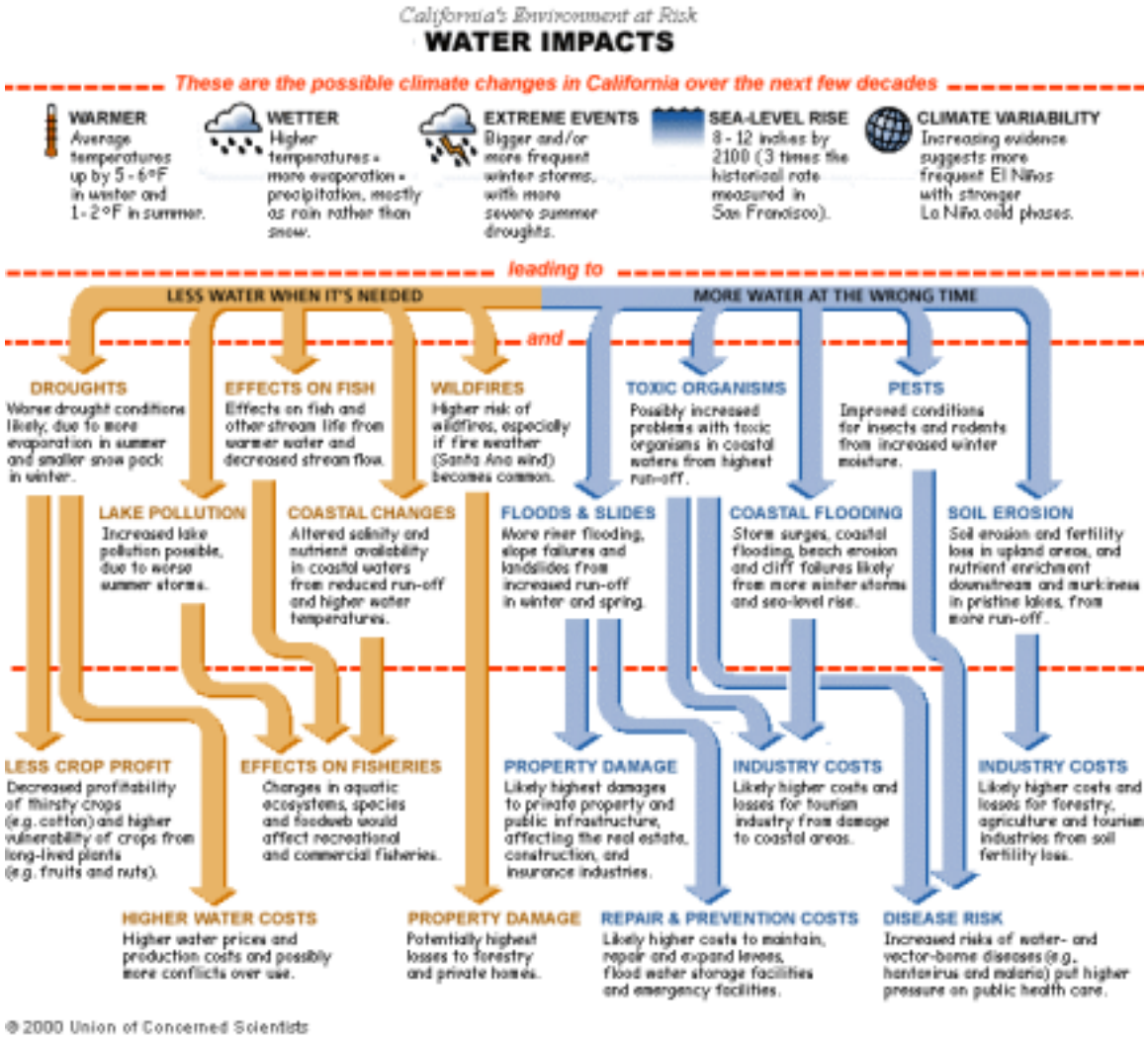
Paving options exist to provide permeability and reduce runoff. Two examples are shown below.

Courtesy of Pavestone Co.

Courtesy of Hastings Pavement Co.

Public Education

The Union of Concerned Scientists developed an interesting web-based tool to represent the interactions and relationships between various aspects of climate change and water systems. It is captured below in a static form. On the web, the linkages and information is interactive. The web site is: http://www.ucsusa.org/pixcc/diafull.gif



Re-Operation of Water Systems

It will likely be necessary to reconsider operating rules for major water supply systems. The water sector report, citing Lettenmaier and Sheer, noted the "sensitivity of the California State Water Project to GCM-derived scenarios of climate change under current operating rules. They concluded that changes in operating rules might improve the ability of the system to meet delivery requirements, but only at the expense of an increased risk of flooding. This kind of trade off is now being seen in a broader set of analyses."[99]

The IPCC calls for a systematic reexamination of engineering criteria, as also noted in the water sector report:[100]

> The IPCC urged water managers to begin "a systematic reexamination of engineering design criteria, operating rules, contingency plans, and water allocation policies" and states with "high confidence" that "water demand management and institutional adaptation are the primary components for increasing system flexibility to meet uncertainties of climate change."[101] This emphasis on planning and demand management rather than construction of new facilities marks a change in traditional water-management approaches, which in the past have relied on the construction of large and expensive infrastructure.

Policy Strategies for Multiple Benefits and No Regrets Responses

California has developed a number of programs and policies to respond to the issue of climate change and variability. The state has invested millions of dollars in climate change research, and it is planning to continue this effort in order to build and maintain the scientific basis for informed policy approaches.

A number of state agencies are actively engaged in research and information dissemination of the issue. As noted above, the California Department off Water Resources is planning a chapter in the state's water plan to address climate change. Other agencies, including the Office of Health Hazard Assessment within CalEPA, are developing information and programs to build an understanding of the issues.

Local governments and non-profit organizations in the state are also engaged. As the Southwest assessment notes: "Urban managers and political bodies will need to enhance their understanding of the interplay between climate and social process in order to assure their city's continued viability and prosperity."[102] The "Cool Roofs" program described above, for example, is being promoted by the non-profit Local Government Commission.

Finally, as noted throughout this assessment report, a number of federal agencies have been extremely helpful in providing scientific information and undertaking research that expands our understanding of the issues. As should be clear, the partnership and collaboration among a wide variety of stakeholders has been invaluable in this assessment process.

This section briefly reviews several programs in California that are dealing with climate change issues.

California Energy Commission

The California Energy Commission (CEC) is the lead state agency for addressing global climate change issues. Willam A. Keese, Chairman, California Energy Commission, commented on the state's efforts over the past two decades:[103]

> California's major energy policies over the past 20 years were designed to respond to energy and air quality issues affecting the state's economy and environment. Adopting these "no-regrets" policies -- including improving energy efficiency, reducing regulated pollutants and developing renewable energy resources. California is a leader in developing renewable energy resources, and since the late 1970s, California has led the nation in promoting energy efficiency in buildings and appliances, supported by building and appliance regulations that exceed federal standards; utility energy efficiency programs; and state government programs, including loans for energy efficiency measures; training programs for builders, manufacturers, and service technicians; and public and classroom education.

Greenhouse Gas Inventory

In 1998 the CEC published a report entitled: *1997 Global Climate Change Report: Greenhouse Gas Emissions Reductions Strategies for California* under the auspices of the U.S. Environmental Protection Agency's Climate Change Partnership Program.[104] The report analyzes greenhouse gas emission sources in California, explores the status of emission reduction strategies, and provides an update on policies to address climate changes previously discussed in the Energy Commission's 1991 global climate change report.[105]

California Climate Registry

In 2000, California established a registry for greenhouse gas emissions managed by a new non-profit organization for the state.

California Climate Registry[106]

Senate Bill 1771, chaptered in September of 2000, specified the creation of the non-profit organization, the California Climate Action Registry (California Registry). The California Registry will help various California entities' to establish greenhouse gas (GHG) emissions baselines. Also, the California Registry will enable participating entities to voluntarily record their annual GHG emissions inventories. In turn, the State of California will use it best efforts to ensure that organizations that voluntarily inventory their emissions receive appropriate consideration under any future international, federal, or state regulatory regimes relating to GHG emissions.

On October 13, 2001, Governor Davis signed California Senate Bill 527 (SB 527). This bill requires the California Energy Commission to provide guidance to the California Registry on a number of issues, such as, developing GHG emissions protocols, qualifying third-party organizations to provide technical assistance, and qualifying third-party organizations to provide certification of emissions baselines and inventories.

Policy Challenges: Overcoming Market and Institutional Barriers

If all these multiple benefits are available, why haven't we taken advantage of them? This is a reasonable question, and there are several parts to the answer. One is that we often fail to recognize, and account for, the benefits that result from smart investments. Daylighting in buildings, for example, saves energy, improves performance and test scores in schools and sales in commercial space, and reduces absenteeism in businesses. These are ample reasons to improve building designs. But daylighting also reduces peak energy demands, reduces air quality emissions from power production, and reduces greenhouse gas emissions. Often, we're just not counting all the benefits.

Another reason is that there are barriers, both market and human/institutional, that get in the way. Professor Stephen DeCanio, Senior Staff Economist for President Reagan's Council of Economic Advisers, notes: [107]

> …to discard the baggage carried by most economists (the author confesses membership of that much-maligned group) that immersion in a market environment guarantees efficient behavior by the market participants. Much of modern economic theory practically *defines* efficiency as the outcome of competitive market exchanges. But the bloodless "competition" of mathematical general equilibrium models bears only a partial relationship to the actual experience of real firms.

DeCanio points out that beyond market failures, human behavior and institutions also lead to lost opportunities (or "sub-optimal allocation" of scarce resources).

As the Southwest assessment notes, improving market signals by utilizing full-cost accounting would be a useful thing to do:[108]

> A major contribution to managing the consequences of climate variability would be to increase economic efficiency while protecting the environment through introduction of full-cost accounting methods[109] and changes in government subsidy practices.[110]

California's efforts to cope with and adapt to climate change must incorporate an understanding of the market and institutional barriers to otherwise cost-effective and useful response strategies. One valuable approach to this challenge is the kind of multi-stakeholder dialogue that has occurred as part of this assessment. By facilitating communication across various boundaries, scientists, decision-makers, and other parties can work together to find appropriate strategies and approaches.

Regional Scale Research and Responses

There are several reasons why California should move forward with state-level efforts to address the potential impacts of climate change as a complement to, not a replacement for, other important national programs.

1. Every region is unique in both its environmental setting and in its social and economic context. There are important assets in the state and region that can be brought to bear on the climate change issue. Both impacts and solutions are a function of the environmental and social context, and it is important to explore the specific approaches that fit the region.

2. People relate to local and regional impacts, and they can also relate to local solutions. There is a greater potential for buy-in for programs at the regional level than at the national or international levels. California-specific droughts and floods, snowpack and water supplies, and landslides and coastal erosion, can be addressed in a different context.

3. There is in fact a "community" of interested parties who tend to know each other and who can work together. This was evident in the workshop business representatives, resource managers, and experts from government agencies talked with university researchers, NGOs and others about

issues and response options. By focusing on these natural communities of common interests we can develop policy approaches that meet immediate as well as long-term needs and concerns.

4. Finally, regional efforts engage people where they live, and they utilize expertise from a wide variety of stakeholders who have a direct concern with the results.

Statutory Authority for Emergency Response

There is, unfortunately, a need to anticipate emergency situations arising from impacts of climate change and variability. The governor is authorized by the *Emergency Services Act* to proclaim a state of emergency when conditions of disaster or extreme peril exist. According to the act:[111]

> These conditions of emergency must be beyond the control, or likely control, of the services, personnel, equipment and facilities of any single city or county. The emergency must also require the combined forces of a mutual aid region to combat. Generally, the act is triggered by a local emergency proclamation and a request to the Governor to proclaim an emergency.

Some of the scenarios set forth above, particularly in cases of extreme events such as floods, fires, and droughts, would require such action. These situations may arise without climate change of course. A part of the planning process in response to the potential impacts of climate change should be an improved understanding of the circumstances under which climate change may increase either the probability or intensity of an emergency situation. Timely information on weather events, like that provided by NOAA during the El Niño event in the late 1990s, would be an example of effective response strategies.

Specific measures may be required to deal with impacts on infrastructure and natural resource systems. For example, California's Water Code authorizes public and private water purveyors to declare a water shortage emergency and to adopt regulations and restrictions to conserve water.[112]

> The governing body of a purveyor may declare a water shortage emergency whenever it determines that consumers' requirements cannot be satisfied without depleting the water supply to the extent that there would be insufficient water for human consumption, sanitation, and fire protection. The governing body may adopt regulations and restrictions on water delivery and use to conserve water for the greatest public benefit, with particular regard to domestic use, sanitation, and fire protection. The regulations may provide for connection moratoria. The California Department of Health Services has the authority to impose terms and conditions on permits for public drinking water systems to assure that sufficient water is available. This includes the authority to require an agency to continue its moratorium on new connections.[113]

Summary

Numerous opportunities exist to respond to climate change and variability through “no regrets” investments in measures that also deliver substantial benefits to society. Exploiting these strategies will yield *multiple benefits* for the economy, society, and the environment in addition to helping reduce negative impacts due to climate change. Policies that incentivize and encourage these sensible investments exist and can be expanded.

California should examine opportunities for cost-effective applications of technology and technique, implemented by private- and public-sector actors, to achieve multiple benefits for climate change as well as for the environment, economy, and society. We should also consider ways these benefits could be supported and encouraged by policy at all levels of government. An appropriate next step would be the development of specific policy recommendations to leverage opportunities.

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Challenge for the Next Century (1998) are also useful sources. Finally, the Water Education Foundation has done a nice job of summarizing the issue in several publications including a "Layperson's Guide to Water Marketing" by Josh Newcome and Elizabeth McCarthy, and the March/April issue of their magazine Western Water, also by Newcome. See: California State Water Resources Control Board, 1999. *A Guide to Water Transfers*, Division of Water Rights, California Environmental Protection Agency, Draft Document, July 1999. At http://www.waterrights.ca.gov/watertransferguide.pdf ; Legislative Analyst's Office, 1999. *The Role of Water Transfers in Meeting California's Water Needs* September 8, 1999. http://www.lao.ca.gov/090899_water_transfers/090899_water_transfers.html ; Pacific Institute for Studies in Development, Environment, and Security; 1998. *California Water Transfers: An Evaluation of the Economic Framework and A Spatial Analysis of Potential Impacts.* www.pacinst.org *;* Vaux, Henry and Richard Howitt, 1984. *Managing Water Scarcity: An Evaluation of Interregional Transfers.*; Phelps, Moore, and Graubaurd, 1978. Efficient Water Use in California's Water Rights, Water Districts, and Water Transfers. RAND.; National Research Council (NRC). 1992. Water Transfers in the West: Efficiency, Equity, and the Environment. National Academy Press. Washington, DC.; Western Water Policy Review Advisory Commission. 1998. Water in the West: Challenge for the Next Century. National Technical Information Service. Springfield, VA.; Newcome, Josh, and Elizabeth McCarthy, 2000. Water Marketing, Water Education Foundation, Layperson's Guide, Sacramento, CA.; Newcome, Josh, 2001. "Is the California Water Market Open for Business?", Western Water, Water Education Foundation, March/April 2001.

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VI. Research Priorities for California

Research Recommendations

Research recommendations are provided here in detail for four key areas of climate impact research and analysis: ecosystems, water systems, modeling regional climate change, and the economics of adaptation. There are other research topics equally deserving of priority that are not listed here. The inclusion of these specific topics is not intended to indicate that others are less important. This assessment was limited in the scope of topics which could be examined in the time available. As such, the research issues identified should be viewed as a sub-set of a broader research agenda to be developed. It is hoped that on-going assessment efforts will expand the list of important research areas and topics.

The research topics identified here are drawn from the work of the California Energy Commission's PIER program. Credit for the development of these lists is as Follows: Rebecca Shaw, Stanford, ecosystems; Maurice Roos, Department of Water Resources, water; Larry Gates, Lawrence Livermore National Lab, climate modeling,; and Alan Sanstad, Lawrence Berkeley National Lab, economics. The lists have been adapted for this assessment.

Ecosystems

Issue Statement
There is a need for improved methods, tools, and data that will support better understanding of the effects of climate change on California's ecosystems.

Background
California's diverse natural and managed ecosystems provide a multitude of goods and services that benefit Californians, including marketable products, environmental services such as water purification, recreational opportunities, and aesthetic pleasure. Despite this, California's ecosystems are being lost and degraded at an unprecedented rate, and a steadily increasing population is placing great pressure on natural systems. The result has been habitat destruction, exotic species introductions, community and species losses, and associated decreases in air and water quality and other health factors. The challenge of responding to the pressures on ecosystems is exacerbated by global climate change, which increases atmospheric temperature and changes the timing and magnitude of precipitation. Climate is a major factor controlling the distribution of species and the structure and functioning of ecosystems, so these changes could affect natural systems in novel, dramatic, and unpredictable ways.

Evaluating California ecosystems, and predicting the potential climate change impacts on those systems, requires research in a variety of areas, and the close cooperation of a host of public and private entities. In the short term, research should focus on developing a comprehensive

assessment and monitoring research plan, conducting ecological monitoring, refining climate and vegetation models to make them more predictable in time and space, and collecting data to validate the models' predictive capabilities.

- **Develop and implement ecological assessment monitoring programs.** A literature search would identify useful long-term data sets and gaps to develop a plan that specifies: monitoring locations and methods, criteria/ecological indicators that the data must meet, and how the data would be stored and disseminated. Once this framework is established, monitoring would begin.

  Benefit: This effort would establish an essential baseline database on California ecosystems, from alpine regions to coastal marine systems. These data would provide the basic information necessary for researchers throughout the state in a variety of disciplines to conduct analyses of climate change on California ecosystems.

- **Develop ecological indicators for data collection.** A broad-based Advisory Committee could develop a list of ecological indicators that address California's unique ecosystems. This effort would give priority to developing indicators of ecological capital and indicators of ecological functioning for the 10 major biomes defined by the California Resources Agency, and coordinate them with national indicators. Researchers would then implement the indicators in monitoring efforts.

  Benefit: A standardized set of ecological indicators would enable researchers to compare monitoring data effectively with one another, which would result in much more accurate ecosystem analyses and facilitate cooperative research among different entities.

- **Develop a more accurate regional climate model.** A broad-based Modeling Advisory Committee (composed primarily of modelers) would guide the development of more accurate regional climate models that could adequately address the needs of regional climate modeling for California.

  Benefit: This work would provide the data necessary to begin to predict the ecosystem and societal impacts, both direct and indirect, of climate change on California. Results could be used by any persons interested in assessing the long-term impacts of climate change on ecosystem structure and biodiversity.

- **Develop a rapid method of disseminating regional climate model data.** This effort would assess current methods of disseminating regional climate model data and develop and implement a central, Web-accessible database for regional climate model data.

  Benefit: Evaluating climatic changes on California ecosystems is a complex endeavor, involving research in many disciplines and across many agencies. This effort would enable researchers to readily access information that would otherwise be inaccessible, thereby greatly increasing the resources of all of the entities involved.

- **Expand data inputs to improve ecosystem and species modeling in vegetation models.** Using existing vegetation models, researchers would incorporate inputs that account for the

successional state of the ecosystem, transient states, substrate types, dispersal modes and rates, disturbance regimes, migration corridors, land use change, and CO_2 fertilization. Once complete, researchers would model ecosystems using the additional criteria and disseminate the results.

Benefit: This work would incorporate climate change impacts in vegetation analyses, which would make the policy decisions based on those analyses much more accurate.

- **Compile and analyze existing paleontological data to better understand past ecological responses to climatological change.**
  A literature search of sound paleontological data would illustrate past ecological responses to climatological change. Researchers would analyze that data to determine associations between ecological variables and historical climatological changes, and disseminate the results.

  Benefit: Better understanding past ecological responses to climatological change would help researchers to better evaluate current responses, and would enable policy makers to base decisions on more-probable scenarios.

Water Systems

Issue Statement

There is a need for improved methods, tools, and data to evaluate the effects of climate change on California's water resources and to develop appropriate response strategies.

Background

Climate change is expected to affect the hydrologic cycle and water resources in California—influencing water supply, hydroelectric power, sea level rise, timing and intensity of precipitation, water use, and water temperature. Water resources in California are already stressed from a high and rapidly growing population, and aquatic ecosystems are imperiled by intense competition for limited supplies of fresh water. The impacts of climate change on water systems are expected to further intensify these problems.

Both California's climate and its water delivery systems are among the most varied and complex in the world, and research plans must adequately address the complete portfolio of water systems in the State. In the short term, a high priority should be placed on measurement, monitoring, modeling, and assessment of California's water system. This work would establish a baseline for future assessment and enable researchers to begin to identify potential water challenges likely to be caused by climate change.

- **Support the regular, consistent, and sustained measurement of hydrologically important variables.** This effort would help the National Weather Service's Climate Services Division develop and operate California weather stations as part of its national climate reference network. Research would also focus on increasing hydrologic measurements in the high Sierra snow zone.

Benefit: These stations would provide basic California climate data over the next 50 years, which could be used to research climate change, as well as many other weather issues.

- **Support the processing and dissemination of up-to-date depth-duration-frequency rainfall data.** Researchers would coordinate the collection and revision of depth-duration-frequency rainfall data with the Department of Water Resources (DWR), design and develop a Web-based database to disseminate this data, and coordinate database maintenance with DWR.

  Benefit: Depth-duration-frequency data is used by water engineers and water planners. Updated information would allow them to plan for potential water project needs, while developing data that can be used by climate change researchers.

- **Conduct a simple test of the impact on water supply of a 3° warmer climate scenario, with the expected changes in snowmelt volume.** Using DWR's CALSIM model, researchers would test the impact of a 3° warmer climate scenario on California's water supply, then confirm the estimates with the UC Davis CALVIN model.

  Benefit: This research would give planners a rough estimate of whether California's Central Valley Project and State Water Project system could accommodate potential flooding brought on by climate change.

- **Conduct detailed tests of the impact of a 3° warmer climate scenario on water supply, with the expected changes in snowmelt volume.** This effort would identify the best model for developing input to the CALSIM model, and use that model to run a more detailed test of the impact of a 3° warmer climate scenario on water supply.

  Benefit: This research would give planners a more detailed estimate of whether California's CVP-SWP system could accommodate potential flooding brought on by climate change, and would produce year-by-year results over a long hydrologic base period.

- **Support the development of global climate models that can better predict future precipitation in California.** This effort would help the University of California and U.S. National Lab experts analyze the results of newer global climate model runs in terms of their application to California.

  Benefit: Researchers would be better able to simulate historical precipitation and predict future precipitation, and thereby better evaluate various climate change scenarios on water systems.

- **Use empirical and satellite techniques to confirm the stability of the datum of the Golden Gate tide gage.** Researchers would compare the datum elevation of the gage with nearby benchmarks sited on solid rock, and then compare the precise vertical elevations using a satellite GPS system.

Benefit: Confirming the stability of this key reference point for a multitude of sea level determinations would validate its accuracy and help ensure the reliability of research based on its data.

- **Conduct a thorough survey of all the tide gage data and any other sea level references along the California coast.**

  Benefit: This survey would help researchers determine trends in sea level in recent decades.

- **Measure current evapotranspiration to compare current data with earlier data.** This effort would identify existing lysimeters in California, reinstall or reoperate lysimeters at Davis and Five Points, and maintain any others. Researchers should maintain lysimeter operation for ten years, to account for seasonal and yearly natural variations.

  Benefit: These lysimeters would enable researchers to better evaluate whether evapotranspiration (ET) rates have changed since data was taken in the 1960s and 1970s, to determine whether groundwater recharge and agricultural water use may be affected.

- **Assess likely changes in ET in a year 2050 or 2100 scenario with warmer average temperatures and higher carbon dioxide content of the atmosphere.** Researchers would obtain reasonable median-type regional projections of weather, primarily temperature, from GCM modelers.

  Benefit: Experts in plant water consumption and land and water use analysts at DWR would use these data to estimate likely future ET rates for the major California crops, by region.

- **Conduct a systematic review and evaluation of flood protection adequacy in major multipurpose flood control reservoirs under projected climate scenarios.** Researchers would conduct a systematic review and analysis of the likely increase in flood control brought about by climate change, determine the feasibility of expanding flood control space in reservoirs deemed inadequate, and determine whether changes in flood operation rules can help to handle bigger floods.

  Benefit: This information would help state water planners ensure that future projects adequately meet the state's water needs.

- **Model water temperatures in both regulated rivers and natural streams.** Researchers would identify appropriate rivers to model, collect basic temperature data at various depths in existing reservoirs to calibrate models, and then model water temperatures in the rivers and streams selected. They would also evaluate the effectiveness of potential countermeasures to unacceptable temperatures.

  Benefit: This work would help identify rivers where altered temperatures may be affecting ecosystems and help researchers develop effective mitigation measures.

Modeling Regional Climate Change

Issue Statement

It is necessary to develop more powerful regional climate models to address local or site-specific variables as part of the climate change impact assessment process in California, and to design and implement a coordinated regional climate modeling program for the State.

Background

Climate changes in California, especially in the winter precipitation, may have serious impacts on the state's water and energy supply; whereas changes in coastal and regional climates may affect the state's economy and resources in significant ways. There is considerable uncertainty surrounding possible future climate changes in California, and it is expected that improved high-resolution regional models will be able to portray the magnitude and distribution of future climate changes in California more accurately. Regional climate modeling provides a more detailed spatial depiction of possible future climate changes than that provided by global models, and bridges the gap between the large-scale and the local scale—on which most impacts of climate change occur. This information is crucial in California, where complex mountain ranges and extended coastline support a variety of regional and local climates. A coordinated regional climate modeling program for California will be an important and necessary tool for addressing climate change in the state.

In the short term, a balanced research program that focuses on the evaluation and intercomparison of high-resolution climate models for California, the development of improved statistical downscaling techniques for hydrologic applications, and the assembly of a regional California climate databank is recommended. This research will reduce the uncertainties involved in projecting future regional climate changes in California and provide guidelines for the more effective management of the state's water and energy resources, in the face of the expected increases in population and development.

- **Design a model intercomparison protocol.** This research would define a domain for California regional climate models (RCMs), select a forcing atmospheric GCM, determine a simulation length and resolution, and identify and document participating RCMs.

  Benefit: This protocol would enable modelers to compare models systematically.

- **Perform control simulations and analyze results.** Researchers would run a selected GCM at high resolution (50km); then repeat the run with selected imbedded RCMs at high resolutions (50km, 20km). They would then determine the systematic errors of the GCM and analyze the systematic errors of the RCMs in simulating mean and variability of selected variables over diurnal, seasonal, interannual and decadal time scales, including occurrence of coastal and valley fog, and extreme precipitation events

  Benefit: This research would identify each model's characteristic errors, and determine the statistical confidence with which regional California climate changes can be simulated.

- **Evaluate downscaling methods.** This effort would determine the relative accuracy of alternative downscaling techniques, and compare performance with comparable regional models.

  Benefit: This work would help researchers determine the accuracy of various methods for statistically downscaling global climate model data to a regional scale.

- **Document uncertainty of hydrologic applications.** Researchers would evaluate models to determine the sensitivity of selected hydrologic variables to downscaling errors and determine the sensitivity of hydrologic variables to resolution.

  Benefit: This work would enable researchers to better determine the accuracy of hydrologic data outputs.

- **Develop California climate database.** Researchers would **c**ollect all available local and regional climate data, document the data, and place it into a Web-accessible database.

  Benefit: A comprehensive California climate database would enable researchers to calibrate regional climate models. Easy data accessibility would speed research and save limited research funds.

- **Develop data access system.** This research project would develop software for data storage, access, diagnosis, and display and distribute it to the research community.

  Benefit: This software would enable all researchers to access, display, and manipulate climate change data.

The Economics of Climate Change Adaptation in California

Issue Statement

There is a need for new tools, methods, and empirical study that can be used to analyze the complex economic problems of adapting to climate change in California, and to provide a sound basis for decision-making.

Background

Rapid and/or extreme shifts in the climate system could be substantial and costly for California. Researchers have examined the economics of climate change over several decades; however, much is still unknown about the costs associated with climate impacts on California and on the measures to mitigate them. In particular, research gaps exist in the areas of greenhouse gas abatement, the promotion of energy efficiency, and how technological change can reduce the costs of addressing climatic change.

The standard economic methods and techniques that have been applied to the problem are still insufficient to fully address the issue. In the short term, a priority on basic research to improve these tools, and thereby develop improved technical foundations for the state's climate-related analysis and policy making, is recommended.

- **Build an aggregate agent-based model of the California economy that includes representations of large-scale climate change impacts.** Once built, researchers can link this model with existing modeling tools to analyze strategies under "deep uncertainty" for climate change adaptation and GHG mitigation in California.

  Benefit: These new models and economic tools would help economic analysts address fundamental economic uncertainties, future climate and economic scenarios, and responses to rapid, severe, and unanticipated climate impacts.

- **Conduct theoretical and empirical research on energy-related decision-making using a behavioral economics approach.** Researchers would examine how advances in behavioral economics could be applied to better include energy-efficiency in economic analyses. A related research effort would construct and econometrically estimate or calibrate one or more models of energy-efficiency investment, incorporating relevant concepts and techniques.

  Benefit: This research would help identify how energy-efficiency investment decisions are made and their implications for policy.

- **Conduct econometric research on endogenous technological change and "learning" effects related to energy technology in California.** Researchers would build or adapt a computational model for energy-technology scenario analysis under uncertainty.

  Benefit: This research would identify how price-induced innovation, learning effects, and government policies have affected trends in energy efficiency in the California economy. As a result, researchers would be able to better project future trends and analyze policies to promote technology adoption.

- **Develop a strategy of "harmonized options" for integrated air quality enhancement and greenhouse gas abatement in a cost/benefit framework.** This effort would formulate strategies for integrated air quality and GHG abatement policies in California and estimate their costs and benefits. It would also incorporate the estimates into state-economy-wide integrated mitigation assessments.

  Benefit: When implemented, these integrated strategies would be designed to simultaneously improve regional air quality and reduce greenhouse gas emissions.

- **Incorporate uncertainty and the possibility of rapid and/or severe climate change into the economic models currently used to assess impact costs.** This work would estimate economic impacts of climate change on California agriculture, taking account of water infrastructure impacts; conduct valuation studies of the non-market California impacts of climate change.

  Benefit: This research would advance economic modeling of sector-specific climate change impacts, and the role of adaptation in those changes. It would also help researchers estimate the value of non-market climate change effects on California.

- **Empirically assess the recent, current, and potential future impacts of information technology on energy trends in the California economy.**

  Benefit: This research would help decision makers analyze energy use and formulate policy decisions more effectively, based on sound information.

Appendix

Appendix 1 **Key Findings of the US National Assessment Synthesis Report** _____ A-1

Appendix 2 **Stakeholder Involvement in the Regional Assessment** _____ A-4
Meetings and Presentations

Appendix 3 **California Regional Workshop** _____ A-7
Steering Committee _____ A-8
Advisory Committee _____ A-10
Workshop Agenda _____ A-12
Workshop Participants _____ A-18

Appendix 1

Key Findings of the US National Assessment Synthesis Report

Key Findings

Climate Change Impacts on the United States

Report for the United States Global Change Research Program

1. Increased warming
Assuming continued growth in world greenhouse gas emissions, the primary climate models used in this Assessment project that temperatures in the US will rise 5-9ºF (3-5ºC) on average in the next 100 years. A wider range of outcomes is possible.

2. Differing regional impacts
Climate change will vary widely across the US. Temperature increases will vary somewhat from one region to the next. Heavy and extreme precipitation events are likely to become more frequent, yet some regions will get drier. The potential impacts of climate change will also vary widely across the nation.

3. Vulnerable ecosystems
Many ecosystems are highly vulnerable to the projected rate and magnitude of climate change. A few, such as alpine meadows in the Rocky Mountains and some barrier islands, are likely to disappear entirely in some areas. Others, such as forests of the Southeast, are likely to experience major species shifts or break up into a mosaic of grasslands, woodlands, and forests. The goods and services lost through the disappearance or fragmentation of certain ecosystems are likely to be costly or impossible to replace.

4. Widespread water concerns
Water is an issue in every region, but the nature of the vulnerabilities varies. Drought is an important concern in every region. Floods and water quality are concerns in many regions. Snowpack changes are especially important in the West, Pacific Northwest, and Alaska.

5. Secure food supply
At the national level, the agriculture sector is likely to be able to adapt to climate change. Overall, US crop productivity is very likely to increase over the next few decades, but the gains will not be uniform across the nation. Falling prices and competitive pressures are very likely to stress some farmers, while benefiting consumers.

6. Near-term increase in forest growth
Forest productivity is likely to increase over the next several decades in some areas as trees respond to higher carbon dioxide levels. Over the longer term, changes in larger-scale processes such as fire, insects, droughts, and disease will possibly decrease forest productivity. In addition, climate change is likely to cause long-term shifts in forest species, such as sugar maples moving north out of the US.

7. Increased damage in coastal and permafrost areas
Climate change and the resulting rise in sea level are likely to exacerbate threats to buildings, roads, powerlines, and other infrastructure in climatically sensitive places. For example, infrastructure damage is related to permafrost melting in Alaska, and to sea-level rise and storm surge in low-lying coastal areas.

8. Adaptation determines health outcomes
A range of negative health impacts is possible from climate change, but adaptation is likely to help protect much of the US population. Maintaining our nation's public health and community infrastructure, from water treatment systems to emergency shelters, will be important for minimizing the impacts of waterborne diseases, heat stress, air pollution, extreme weather events, and diseases transmitted by insects, ticks, and rodents.

9. Other stresses magnified by climate change
Climate change will very likely magnify the cumulative impacts of other stresses, such as air and water pollution and habitat destruction due to human development patterns. For some systems, such as coral reefs, the combined effects of climate change and other stresses are very likely to exceed a critical threshold, bringing large, possibly irreversible impacts.

10. Uncertainties remain and surprises are expected
Significant uncertainties remain in the science underlying regional climate changes and their impacts. Further research would improve understanding and our ability to project societal and ecosystem impacts, and provide the public with additional useful information about options for adaptation. However, it is likely that some aspects and impacts of climate change will be totally unanticipated as complex systems respond to ongoing climate change in unforeseeable ways.

National Assessment Synthesis Team
Climate Change Impacts on the United State.
Report for the United States Global Change Research Program
Cambridge Univ. Press. 2001

The full report is available at:
http://prod.gcrio.org/nationalassessment/

Appendix 2

Stakeholder Involvement in the Regional Assessment

The California Regional Assessment process included presentations, meetings, and discussions with various stakeholders. Listed below are the major presentations and key meetings.

California Regional Assessment Workshop, Santa Barbara(March 1998)
EPA Climate Impacts Meeting Phoenix, (September 1998)
Air and Waste Management Annual Meeting, Washington DC (October 1998)
Potential Impacts on Water Resources in the West (February 1999)
Workshop for the Great Basin Regional Analysis, National Center for Ecological Analysis and Synthesis (Santa Barbara)
EPA Workshop on Multiple Benefits (March 1999)
Climate Change and Land Use Planning, EPA Workshop (Davis)
Aspen Global Change Institute Summer Session on Urban Impacts (July 1999)
(Co-chaired the AGCI Session with Tom Wilbanks, Oak Ridge National Laboratory),
Advanced Technology Program, United States Department of Commerce (October 1999)
Water, Technology, and Climate Change (San Jose)
Silicon Valley Manufacturer's Association (December 1999)
Case Studies and Climate Change (NASA/AMES Research Center)
Kaweah-Tule Watershed Management Council (January 2000)
Climate Change, Watersheds and Agriculture (Visalia)
World Environment Center International Environment Forum (February 2000)
Environmental Policy and Climate Change (Santa Barbara)
World Resources Institute (March 2000)
Credible Science: The US Impacts Assessment and Communication (Washington DC)
UCSB Geography Colloquium (March 2000)
The USGCRP Assessment of Climate Impacts: The California Region (Santa Barbara)
California Resources Agency (March 2000)
Continuing Resource Investment Strategy Project, Potential Climate Impacts, (Sacramento)
CERES - Coalition for Environmentally Responsible Economies (April 2000)
Potential Impacts of Climate Change on Water Resources (San Francisco)
White House Office of Science and Technology Policy (OSTP) (May 2000)
Presentation, President's Science Advisor / White House Task Forces (Washington DC)
Udall Center Conference on Technology and Conflict Resolution (May 2000)
Climate Change Impacts Assessment and Urban Planning (Tucson)
PACLIM (Pacific Climate) (May 2000)
Potential Impacts on Climate Change and Variability for California (Catalina Island)
Electric Power Research Institute (EPRI) / California Energy Commission (June 2000)
Workshops on Climate Impacts in California (Sacramento)
NASA/RESAC Meeting, Earth Sciences Division, Berkeley Lab (June 2000)
Water Education Foundation (July 2000)
Potential Impacts of Climate Change and California Water Law (San Diego)
PEW Center on Climate Change (July 2000)
Potential Impacts on Climate Change and Variability for California (Washington DC)
MEDEA / US Intelligence Briefing for the President (August 2000)

Climate impact analysis and the US Assessment (Preparatory meeting briefing for incoming president) (Santa Barbara)

US Environmental Protection Agency (September 2000)
Keynote for EPA's Climate Programs Retreat (West Virginia)

Haas Business School, UC Berkeley, Future 500 Conference (October 2000)
Climate Change and Corporate Leadership (Berkeley)

EPA Workshop on Multiple Benefits (October 2000)
Climate Change and Green Building, EPA Workshop (Santa Barbara)

American Nuclear Society Annual Meeting (November 2000)
Potential Impacts on Climate Change and Variability for California (Washington DC)

Oberlin College (November 2000)
Guest Lecture on Potential Impacts of Climate Change in California (Oberlin, Ohio)

National Water Research Institute (October 2001)
Urban watershed management strategies and climate change (Costa Mesa)

Electric Power Research Institute (EPRI) / California Energy Commission (January 2001)
Meeting on Climate Impacts in California (Sacramento)

California Senate, Select Committee on Delta Resources and Development (November 2001)
Global Climate Change and Its Potential Effects on the Sacramento-San Joaquin Delta (Sacramento)

California Assembly, Select Committee on Air and Water Quality (November 2001)
Potential Impacts of Global Climate Change and Variability on California (Santa Monica)

Resource Landowners Coalition (November 2001)
The California Water Plan and Potential Impacts of climate change in California (Sacramento)

California Association of Water Agencies (ACWA) (November 2001)
Impacts on Climate Change and Variability for California (San Diego)

Public Officials for Water and Environmental Reform (December 2001)
Impacts on Climate Change and Variability for California (Los Angeles)

Other meetings:

Metropolitan Water District of Southern California (MWD)
(Briefing for General Manager and top management)

California Energy Commission
(numerous meetings with Commissioners and staff)

California Resources Agency
(numerous meetings with the Resources Secretary and staff)

California Department of Water Resources
(numerous meetings with staff and with staff / business and other stakeholders)

California Continuing Resource Investment Strategy Project (CCRISP) / Legacy
(keynote for the program launch and numerous meetings with staff)

California EPA
(numerous meetings with the Secretary and staff)

California Office of Environmental Health Hazard Assessment
(meetings with staff and advisory role for indicators)

California Department of Food and Agriculture
(meetings with staff)

US Environmental Protection Agency
(advisory role for administrator, Region 9, on climate change, meetings with staff)

Global Business Network

(discussions on impacts to business, scenario planning options for California, GBN provided keynote for the California Workshop)

California Environmental Dialogue

(numerous discussions with California's leading businesses regarding climate change and related topics)

Various Businesses

(individual meetings with numerous companies in the region regarding potential impacts of climate change and variability)

Farmers

(individual meetings with farmers in different parts of the region regarding potential impacts of climate change and variability)

Major Landowners

(individual meetings with major landowners in the region regarding potential impacts of climate change and variability)

Environmental Organizations

(individual meetings with numerous organizations in the region regarding potential impacts of climate change and variability)

Pew Center

(meeting with the director of the Pew Center regarding the California Assessment work)

International Network of Resource Information Centers

(several meetings with IPCC participants and others involved in climate impact analysis from various countries)

Western Governors' Association

(numerous meeting with the WGA and with Governors and their staff regarding climate change)

Asia Development Bank

(discussion of climate change in the context of long-range planning for the bank)

Department of Energy

(discussions regarding climate change)

Society for Ecological Restoration

(discussion regarding climate change and ecological impacts and the role of restoration)

Appendix 3

California Workshop on Climate Variability and Change

California Regional Assessment
USGCRP

Santa Barbara, California
March 9–11, 1998

Workshop Convener:
National Center for Ecological Analysis and Synthesis
University of California, Santa Barbara
735 State Street, Suite 300
Santa Barbara, CA 93101-3351

Sponsor:
National Science Foundation

Workshop Steering Committee Chair:
Jeff Dozier
Donald Bren School of Environmental Science and Management
University of California, Santa Barbara

Workshop Coordinator:
Robert Wilkinson
Environmental Studies Program
University of California, Santa Barbara

Steering Committee

California Workshop on Climate Variability and Change

Jeff Dozier (Chair, Steering Committee)
Dean, School of Environmental
Science and Management
University of California
Santa Barbara, California

Richard Berk
Professor of Sociology and Statistics
Department of Statistics
University of California
Los Angeles, California

Dan Cayan
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California

Frank Davis
Deputy Director
National Center for Ecological
Analysis and Synthesis
Santa Barbara, California

James Dehlsen
Director
Enron Renewable Energy Corporation
Santa Barbara, California

Nicholas Graham
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California

Peter H. Gleick
Director
Pacific Institute for Studies in Development,
Environment, and Security
Oakland, California

William J. Keese
Chairman
California Energy Commission
Sacramento, California

Charles Kolstad
Professor, Economics and Environmental Studies
University of California
Santa Barbara, California

Jim McWilliams
Institute of Geophysics and Planetary Physics
University of California
Los Angeles, California

John Melack
Professor, School of Environmental
Science and Management
University of California
Santa Barbara, California

Harold A. Mooney
Department of Biology
Stanford University
Stanford, California

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California Regional Assessment

Workshop Program
March 9–11, 1998

MONDAY, March 9

9:00 am - 10:45 am **Santa Ynez** Plenary Session

Welcome to the California Regional Workshop on Climate Change and Variability
Jim Reichman, Director, National Center for Ecological Analysis and Synthesis
University of California, Santa Barbara
Jeff Dozier, Dean, Donald Bren School of Environmental Science and Management
University of California, Santa Barbara, and Chair, Steering Committee for the California Workshop

The California Climate Assessment: Goals and Process for the Workshop
Robert Wilkinson, Coordinator, California Workshop on Climate Change
Lecturer, Environmental Studies Program, University of California, Santa Barbara

Global Climate Change and Variability: The Science of Climate Change and the Assessment Process in the United States
Robert Corell, Director, US Global Change Research Program, and
Assistant Director for Geosciences, National Science Foundation

Modeling Climate Change and Future Climates
Mike MacCracken, Executive Director, National Assessment Coordination Office
US Global Change Research Program

Climatically Sensitive California: Past, Present, and Future Climate
Norman Miller, Staff Scientist, Earth Sciences Division, Lawrence Berkeley Laboratory

Visualizing Climate Change Impacts at the Local Level: A California Case Study
Wil Orr and Hoyt Johnson
Sustainability and Global Change Program, Prescott College
Ashton Shortridge, Researcher
National Center for Geographic Information Analysis, University of California, Santa Barbara

11:00 am -12:00 noon **Santa Ynez** Plenary Session
Socio-Economic Implications of Climate Change for California
Tapan Munroe, Chief Economist, Pacific Gas and Electric Company

12:00 noon - 1:30 pm Lunch **San Rafael**
The Art of the Long View: Creating Scenarios for Alternative California Futures
Peter Schwartz, President, Global Business Network

2:30 pm-5:30 pm Breakout Sessions
Breakout Discussions on Potential Climate Impacts to Human Systems

San Miguel W

1. **Urban Centers and Suburban Sprawl: Growth, and the Impacts of Climate Change**
   Nancy Skinner, Director, International Council for Local Environmental Initiatives
   Paul Wack, Lecturer, Environmental Studies Program, UCSB
   Judy Corbett, Executive Director, Local Government Commission

San Miguel E

2. **Energy Systems**
   Claude Poncelet, Pacific Gas & Electric
   Jan Sharpless, Commissioner, California Energy Commission

Santa Rosa W

3. **Coastal Land Use**
   Jo Bodovitz, The California Trust
   Madelyn Glickfeld, Senior Research Fellow, Claremont Graduate School Research Institute

Santa Rosa E

4. **Community Impacts and Initiatives**
   Andy Lipkis, President, TreePeople
   Catherine McKalip, President's Council on Sustainable Development

Santa Cruz W

5. **Public Education and Information**
   Kelly Sims, Science Policy Director, Ozone Action
   Wilson Orr, Director, Sustainability and Global Change Program, Prescott College

Santa Cruz E

6. **Public Perception of Climate Issues**
   Richard Berk, Professor of Sociology and Statistics, UCLA
   Bud Laurant, Supervisor, San Luis Obispo County

Anacapa W

7. **Impacts and Options for Water Systems**
   Susan Munves, Conservation Coordinator, Environmental Programs
   Maurice Roos, Chief Hydrologist, Department of Water Resources

Anacapa E

8. **Transportation Systems: Mobility and the Climate Issue**
   Thomas Crumm, Manager Envisioning & Alternative Futures Development, General Motors
   Al Sweedler, Professor of Physics, San Diego State University

7:30 pm Dinner **San Rafael**
From Rio to Kyoto: International Policy Process
John Fialka, *Wall Street Journal*

TUESDAY, March 10

9:00 am- 10:30 am **Santa Ynez** Plenary Session

Climate Impacts on the Ecosystem Services
Underpinning California's Economy and Quality of Life

Walter C. Oechel, Director, Global Change Research Group and San Diego State University
Camille Parmesan, Research Scientist, National Center for Ecological Analysis and Synthesis, UCSB
Peter H. Gleick, Director, Pacific Institute for Studies in Development, Environment, and Security

11:00 am-12:30 pm Breakout Sessions
Breakout Sessions on Key Ecosystem Sectors

San Miguel W

1. **New Ecosystem Distributions and Ecotones: Planning for Ecosystems, Habitat, and Preserves for 2050 and beyond**
   Hal Mooney, Professor, Biological Sciences, Stanford University
   Rachael Craig, Kent State University
   Camille Parmesan, NCEAS

San Miguel E

2. **Marine Fisheries and Ecosystems: Coastal Marine Services, Nursery Functions, Pelagic and Blue Water Fisheries, and Effects of Water Temperature Changes and Changes in Upwelling**
   Craig Fusaro, Director, Joint Oil/Fisheries Liaison Office
   George Boehlert, National Marine Fisheries Service

Santa Rosa W

3. **Managing Rangeland, Chaparral, and Oak Woodland Ecosystems for Water Yield, Fire, Grazing, and Habitat**
   Frank Davis, Deputy Director, National Center foe Ecological Analysis and Synthesis

Santa Rosa E

4. **Habitat Conservation Plans (HCP), Natural Communities Conservation Plans (NCCP), and Multiple Species Conservation Plans (MSCP) and Biodiversity in the Context of Climate Change**
   Jim Young, Southern California Edison
   Walter Oechel, Director, Global Change Research Group and San Diego State University

Santa Cruz W

5. **Forestry, Forest Impacts, and Climate Change**
   William Stewart, Director, California Department of Forestry and Fire Protection
   Tom Suchanek, Director, Western Regional Director of NIGEC, at UC Davis

Santa Cruz E

6. **The Dynamics of Water Systems, Inland Water Ecosystems, and Potential Impacts of Climate Change**
   Peter Gleick, Director, Pacific Institute
   John Melack, Professor, Biology and Environmental Science and Management, UCSB

Anacapa W

7. **Agro-Ecosystems and the Impacts of Climate Change**
   Don Ermin, Director, Centers for Water and Wildlands Resources

Anacapa E

8. **Desert Ecosystems: Climate Change Implications for Boundary Shifts and Species Distribution and Composition**
   Kelley Redmond, Desert Research Institute
   Fred Wagner, Director, Ecology Center, Utah State University

12:30 pm - 1:30 pm Lunch **San Rafael**

Special Presentation on the National Institute for Global Environmental Change (NIGEC): Cutting-Edge Research on Impacts of Global Change in the Western U.S.

Ruth Reck, National Director, NIGEC, at UC Davis
Tom Suchanek: Western Regional Director of NIGEC, at UC Davis

2:30 pm - 4:30 pm Breakouts Sessions

Breakout Discussions on Topics of Special Interest and Self-Organized Meetings

(Time is available here for meetings which participants wish to organize themselves to address topics of specific interest.)

San Miguel W

1. **California Greenhouse Gas Emissions Inventory**
   Guido Franco, California Energy Commission

San Miguel E

2. **Regional Ecosystem Impact Studies: Union of Concerned Scientists and the Ecological Society of America**
   Peter Frumhoff, Union of Concerned Scientists

Santa Rosa W

3. **California Pilot Project on the Use of Climate Forecast Information (NOAA)**
   Ants Leetmaa, Director, Climate Prediction Center, NOAA
   Claudia Nierenberg, International Economist, Office of Global Programs, NOAA

Santa Rosa E

4. **Climate Modeling and California: Discussion of the Science**
   Norman Miller, Staff Scientist, Earth Sciences Division, LBL
   Mike MacCracken, Executive Director, National Assessment Coordination Office, US Global Change Research Program

Santa Cruz W

5. **(To Be Determined by Participants)**

Santa Cruz E

6. **(To Be Determined by Participants)**

Anacapa W

7. **(To Be Determined by Participants)**

Anacapa E

8. **(To Be Determined by Participants)**

WEDNESDAY, March 11

9:00 am - 10:30 am **Santa Ynez** Plenary Session

A California Climate Initiative:
Exploring Stakeholder Collaboratives for a Sustainable Future

Jeff Dozier, Dean, Donald Bren School of Environmental Science and Management, UCSB
Jim McWilliams, Professor, Institute of Geophysics and Planetary Physics, UCLA
Larry Papay, Senior Vice President, Bechtel Group
Michael Moore, Commissioner, California Energy Commission

11:00 am-12:30 pm
Breakouts Discussions Exploring Opportunities for Collaboration and Research Priorities Following the Morning Presentations

San Miguel W

1. **Exploring a Program for 2020 Foresight: Building an Alliance**
   Jim McWilliams, Professor, Institute of Geophysics and Planetary Physics, UCLA
   John Wise, Environmental Protection Agency, Region IX

San Miguel E

2. **Redefining Progress: New Technologies and Approaches to Deal With Climate Change**
   Jim Dehlsen, Enron Renewable Energy Corporation
   Maureen Kennedy, Director, Redefining Progress

Santa Rosa W

3. **Creating a California Collaborative to Address Climate Change Issues**
   Jeff Dozier, Dean, Donald Bren School of Environmental Science and Management
   Michael Moore, Commissioner, California Energy Commission

Santa Rosa E

4. **Community-Based Collaboratives to Address Climate Change**
   Kelley Sims, Science Policy Director, Ozone Action
   Blair Henry, Chair, Northwest Council on Climate Change

Santa Cruz W

5. **Developing Strategies to Quantify Potential Costs and Benefits of Climate Change Impacts in California**
   Charles Kolstad, Professor of Economics and Environmental Science and Management, UCSB

Santa Cruz E

6. **Private Sector/Research Institute Collaboratives on Climate**
   Larry Papay, Senior Vice President, Bechtel Group
   Jim Cole, California Institute for Energy Efficiency

Anacapa W

7. **Multiple Benefits of Climate Change Adaptation and Mitigation Strategies**
   Eileen Shea, Center for the Application of Research on the Environment, Institute of Global Environment and Society

Anacapa E

8. **International Dimensions of Climate Change Impacts in California**
   Chris Bernabo, President, Science and Policy Associates
   Claude Poncelet, Pacific Gas & Electric

1:30 pm-3:30 pm **Santa Ynez** Plenary Session

Summary of the Top Issues for California and Plans for Follow-On Activities

Jeff Dozier, Dean, Donald Bren School of Environmental Science and Management, University of California, Santa Barbara, and Chair, Steering Committee for the California Workshop

Robert Wilkinson, Coordinator, California Workshop on Climate Change

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Ralph	Bernstein	Electric Power Research Institute
Joseph	Bodovitz	California Environmental Trust
George	Boehlert	NOAA/NMFS
Barry	Bortnick	Santa Barbara Newspress
Katherine	Boxer Latipow	California Utilities Emergency Association
Gail	Brown	University of California, Santa Barbara
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Edward	Cassano	Channel Islands National Marine Sanctuary
Glennda	Chui	San Jose Mercury News
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Kristin	Coates	
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Monica	Dunne	University of California, Santa Barbara
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Don	Erman	University of California, Davis
Sarah	Fangman	Channel Islands National Marine Sanctuary
Michael	Feinstein	City of Santa Monica
John	Fialka	Wall Street Journal
John	Foster	USEPA
Guido	Franco	California Energy Commission
Ed	Frazier	TRW

Barbara	Freese	Minnesota Attorney General's Offfice
Peter	Frumhoff	Union of Concerned Scientists
Craig	Fusaro	Joint Oil Fisheries Liaison Officer
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Maureen	Kennedy	Redefining Progress
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Catherine	McKalip	President's Council on Sustainable Development
Jeff	McMahon	New Times
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Ruth	Reck	National Institute for Global Environmental Change
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Maurice	Roos	Department of Water Resources
Paul	Rosenstein	City of Santa Monica
Teresa	Rounds	Santa Barbara Museum of Natural History
Steve	Sachs	SANDAG
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California Contribution to the National Assessment on the Potential Consequences of Climate Change for the United States

The overall goal of the National Assessment is to analyze and evaluate what is known about the potential consequences of climate variability and change for the Nation in the context of other pressures on the public, the environment, and the Nation's resources. The National Assessment process has been broadly inclusive, drawing on inputs from academia, government, the public and private sectors, and interested citizens. Starting with broad public concerns about the environment, the Assessment is exploring the degree to which existing and future variations and changes in climate might affect issues that people care about.

The National Assessment has three major components:

1. Regional analyses: Workshops and assessments are characterizing the potential consequences of climate variability and change in selected regions spanning the United States. The reports from these activities address the interests of those in the particular regions by focusing on the regional patterns and texture of changes where people live. Most workshop reports are already available (see http://www.nacc.usgcrp.gov) and regional assessment reports will become available as they are completed.

2. Sectoral analyses: Workshops and assessments are being carried out to characterize the potential consequences of climate variability and change for major sectors that cut across environmental, economic, and societal interests. The sectoral studies analyze how the consequences in each region affect the Nation, making these reports national in scope and of interest to everyone. The sectors being focused on in this first phase of the ongoing National Assessment include Agriculture, Forests, Human Health, Water, and Coastal Areas and Marine Resources.

3. National overview: The National Assessment Synthesis Team has responsibility for summarizing and integrating the findings of the regional and sectoral studies with the broader literature, and then drawing conclusions about the importance of climate variability and change for the United States. Their report is to be available in 2000.

Each of the regional, sectoral, and synthesis activities is being led by a team comprised of experts from both the public and private sectors, from universities and government, and from the spectrum of stakeholders.

California ?????????

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PREPARING FOR A CHANGING CLIMATE • CALIFORNIA

September 2002

Spine should be
sized to fit,
and be an extension
of the cover
background.