


INDICATORS OF CLIMATE CHANGE IN CALIFORNIA

April 2009

Arnold Schwarzenegger
Governor

Linda Adams
Secretary for
Environmental Protection

Joan E. Denton, Ph. D.
Director, Office of Environmental
Health Hazard Assessment

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Compiled and Edited by:
Linda Mazur
Carmen Milanes
California Environmental Protection Agency
Office of Environmental Health Hazard Assessment
Integrated Risk Assessment Branch (IRAB)

Reviewers:
Karen Randles, IRAB
William Dean, Cal/EPA Office of the Secretary
David Siegel, Ph.D., DABT, Chief, IRAB
George Alexeeff, Ph.D., Deputy Director for Scientific Affairs
Allan Hirsch, Chief Deputy Director

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CONTRIBUTORS

John Abatzoglou, San Jose State University
Michael Anderson, Department of Water Resources
Dennis Baldocchi, University of California Berkeley
Hassan Basagic, Portland State University
Rupa Basu, Office of Environmental Health Hazard Assessment
Steven Bograd, NOAA/NMFS, Southwest Fisheries Science Center
Russell W. Bradley, PRBO Conservation Science
Kim Nichols Cahill, Stanford University
Dan Cayan, Scripps Institution of Oceanography
Robert Coats, Hydroikos Ltd.
Michael Dettinger, Scripps Institution of Oceanography
Laura Edwards, Desert Research Institute/Western Regional Climate Center
Marc Fischer, Lawrence Berkeley National Laboratory
Matthew Forister, University of Nevada Reno
Andrew Fountain, Portland State University
Guido Franco, California Energy Commission
Alexander Gershunov, Scripps Institution of Oceanography
Mark Herzog, PRBO Conservation Science
Diana Humple, PRBO Conservation Science
Jaime Jahncke, PRBO Conservation Science
Karen Lutter, California Air Resources Board
Connie Millar, US Forest Service, Pacific Southwest Research Station
Craig Moritz, Museum of Vertebrate Zoology
Bill Peterson, NOAA, Hatfield Marine Science Center
Kelly Redmond , Desert Research Institute/Western Regional Climate Center
William Reisen, University of California, Davis
Maurice Roos, Department of Water Resources
Geoffrey Schladow, University of California, Davis
Franklin Schwing, NOAA, Southwest Fisheries Science Center
Arthur Shapiro, University of California, Davis
William Sydeman, Farallon Institute for Advanced Ecosystem Research
Pieter Tans, NOAA, Climate Monitoring and Diagnostics Laboratory
Webster Tasat, California Air Resources Board
James Thorne, University of California, Davis
Mary Tyree, Scripps Institution of Oceanography
Phillip van Mantgem, U.S. Geological Survey
Anthony Westerling, University of California, Merced
John A. Wiens, PRBO Conservation Science

EXECUTIVE SUMMARY

Environmental indicators are measurements that present scientific information on the status of, and trends in, environmental conditions. They are valuable in tracking changes in the environment, and communicating complex environmental information to a broad audience.

This report presents a compilation of environmental indicators that collectively describe changes to California's climate, the drivers of these changes, and the impacts of such changes on the state. The indicators draw upon data collection, monitoring and studies by state and federal agencies, universities and research institutions.

The most recent assessment of global observational data conducted by the Intergovernmental Panel on Climate Change (IPCC) concludes that the evidence for the Earth's warming is unequivocal, and that this is mostly due to anthropogenic greenhouse gases. The IPCC further concludes that the impacts of climate change on physical systems are seen in increased runoff and earlier spring peak discharge, decreases in snow and ice extent, increases in sea level, and the warming of lakes and rivers. Impacts on biological systems are evident in the earlier timing of spring events, and shifts in the geographical ranges in which plants and animals live.

The global evidence

- **Climate change and its drivers**
  - Warming is unequivocal
  - Mostly due to anthropogenic greenhouse gases
- **Impacts on physical systems**
  - Warming of lakes and rivers
  - Increases in sea level
  - Decreases in snow and ice extent
  - Increased runoff and earlier spring peak discharge
- **Impacts on biological systems**
  - Earlier timing of spring events
  - Shifts in plant and animal ranges

Source: IPCC, Fourth Assessment Report

Changes occurring in California are largely consistent with those occurring globally. In summary, the indicators of climate change in this report show the following:

CLIMATE CHANGE DRIVERS

- Emissions of greenhouse gases have increased since 1990, with carbon dioxide from the combustion of fossil fuels for transportation accounting for the largest proportion of emissions.

- Atmospheric concentrations of carbon dioxide have been increasing in coastal areas of the state, consistent with global trends.

CHANGES IN CLIMATE

- Air temperatures have increased over the past century, with nighttime minimum temperatures showing a greater rate of increase than daytime maximum temperatures. Counties with populations over 1 million are warmer than those with populations under 100,000.

- Summertime temperature extremes, especially at night, have been decreasing over the past half century. Likewise, winter chill hours, a factor critical for fruit trees to produce flowers and fruit, have been decreasing in the fruit growing valleys of California over the same time period.

- Precipitation trends show little change over the past century.

IMPACTS ON PHYSICAL SYSTEMS

- Spring snowmelt from the Sierra Nevada to the Sacramento River has declined over the past century.

- The average amount of water stored in the state's snowpacks is largely unchanged, although snow-water content has declined in the northern Sierra Nevada but increased in the southern Sierra Nevada.

- Glaciers in the Sierra Nevada have decreased in area over the past century.

- Sea levels measured at stations in San Francisco and La Jolla have been rising.

- Water temperatures in Lake Tahoe in the past 30 years, and ocean water temperatures at La Jolla in the past century, are rising. However, water temperatures in the southern Sacramento-San Joaquin River Delta over the past decade have stayed roughly the same.

- Oxygen concentrations are decreasing in California ocean waters.

IMPACTS ON BIOLOGICAL SYSTEMS

- Tree deaths in the Sierra Nevada have increased with rising temperatures.

- The frequency of large wildfires has increased.

- The lower edge of the conifer-dominated forests in the Sierra Nevada has been retreating upslope over the past 60 years.

- The spring and fall arrivals of some migratory birds are changing.

- Small mammals in Yosemite National Park are found today at different elevational ranges compared to earlier in the century.

- Butterflies in the Central Valley have been arriving earlier in the spring over the past four decades.

- Auklet breeding success on the Southeast Farallon Islands off the California coast has been more variable, with unprecedented reproductive failures in 2005 and 2006.

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INDICATORS OF CLIMATE CHANGE IN CALIFORNIA

INTRODUCTION

Climate change is one of today's most formidable challenges. Changes in California's climate -- which have been consistent with global trends over the last fifty years -- represent serious threats to the health, environment, and economy of the State and its residents. Recognizing this vulnerability, the State is taking measures to reduce its greenhouse gas contributions, and to implement strategies for avoiding or managing the potential adverse impacts of climate change (California Climate Change Center, 2006).

This report presents a compilation of indicators that collectively describe changes to the State's climate, and how these changes have impacted physical and biological systems. It builds on the small set of climate change indicators presented in the Environmental Protection Indicators for California (EPIC) Report (OEHHA, 2002). It represents a collaborative effort with the California Energy Commission (CEC), the California Environmental Protection Agency's (Cal/EPA) Office of the Secretary, the Air Resources Board, other State departments, federal agencies, and various universities and research institutions. Research studies sponsored by the CEC's Public Interest Energy Research (PIER) Program served as the basis for many of the indicators. While economic impacts are also anticipated as a result of climate change, such impacts are beyond the scope of this document.

CLIMATE CHANGE: AN OVERVIEW

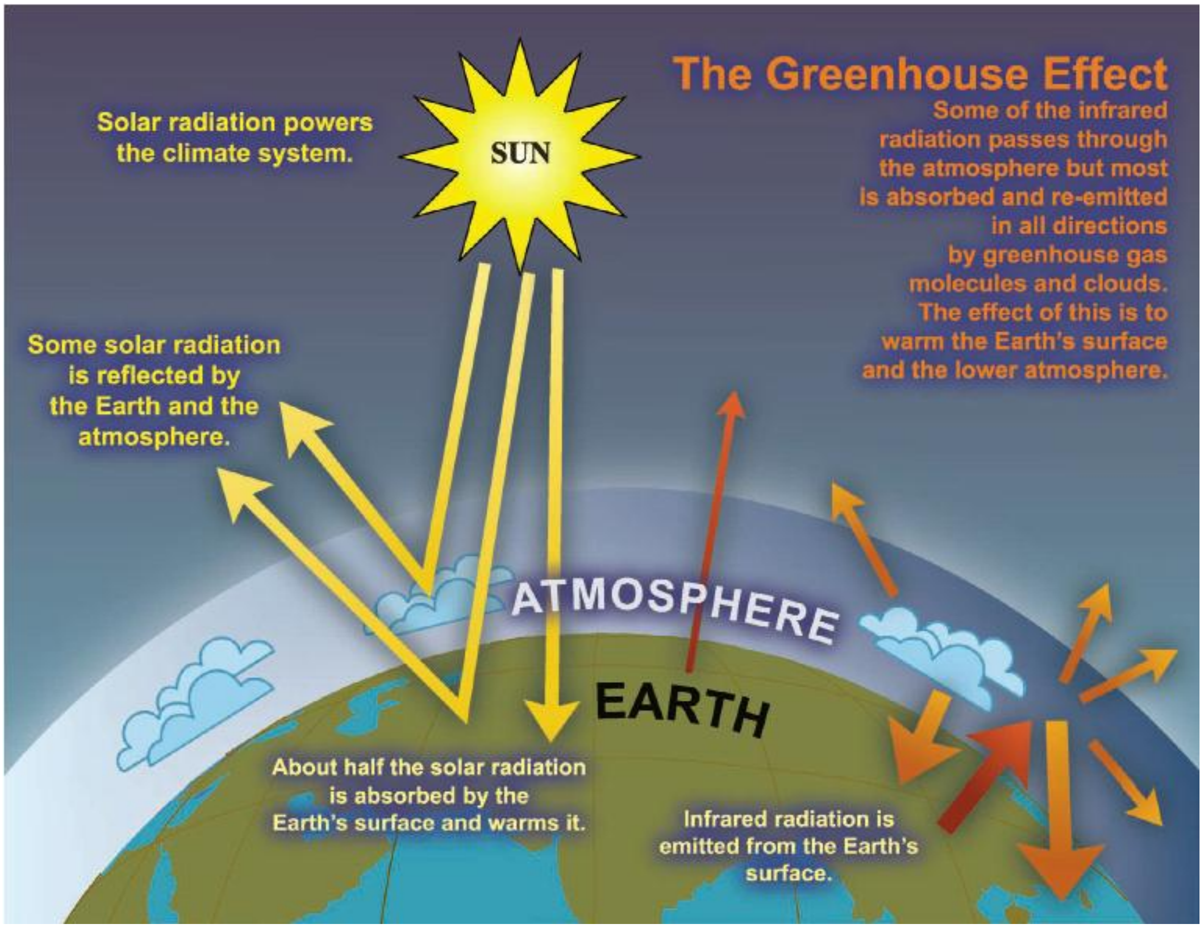
Climate change refers to a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC, 2007b). Such changes may be due to internal processes inherent to the climate system itself, and to influences by external factors. External factors include natural phenomena, such as changes in solar radiation and volcanic activity, as well as anthropogenic or human-induced changes in atmospheric composition.

Observed increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level provide unequivocal evidence that the earth's climate system is warming. In the past century (1906-2005), average global temperatures have increased by about 0.74°C, with the rate of increase from 1956 to 2005 at nearly twice the rate for the century (IPCC, 2007). The ten warmest years on record have occurred since 1995, with the years from 2001 to 2007 making up seven of the eight warmest years (NCDC, 2008). Temperature measurements of lower- and mid-tropospheric temperature show warming rates similar to those observed for surface temperature.

According to the Intergovernmental Panel on Climate Change (IPCC), a scientific body established by the World Meteorological Organization (WMO) and by the United Nations

Environment Programme (UNEP), available scientific evidence supports the conclusion that most of the increased average global temperatures since the mid-20th century is very likely due to human-induced increases in greenhouse gas concentrations (IPCC, 2007a). Greenhouse gases, which are emitted from both natural and anthropogenic sources, include water vapor, carbon dioxide, methane, nitrous oxide, halocarbons, and ozone. These gases play a role in the "greenhouse effect," a natural phenomenon that helps regulate the temperature of the earth (see Figure 1). Solar energy that heats the earth is either radiated back to space, or trapped in the atmosphere by clouds and greenhouse gases. The effect of this is to warm the earth's surface and the lower atmosphere. Human activities, primarily the burning of fossil fuels and clearing of forests, have greatly intensified the natural greenhouse effect, causing global warming. Emissions of greenhouse gases due to human activities have increased globally since pre-industrial times, with an increase of 70 percent between 1970 and 2004 (IPCC, 2007a, b).

Periodic assessments of climate change-related studies conducted world-wide are carried out by the IPCC. These assessments provide a comprehensive, objective, open and transparent evaluation of the latest data relevant to the understanding of the risk of



Source: IPCC, 2007b

Figure 1. An idealized model of the natural greenhouse effect

human-induced climate change, its observed and projected impacts, and options for adaptation and mitigation. IPCC's assessments are generally accepted standard works of reference, and are widely used by policymakers and experts. IPCC's findings have served as the basis for such policy-setting and international agreements as the United Nations Framework Convention on Climate Change and the Kyoto Protocol (IPCC, 2008).

In its most recent assessment, the IPCC concludes that observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases. Data since 1970 have shown that anthropogenic warming has had a discernable influence on many physical and biological systems. These include changes in snow, ice and frozen ground; increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers; warming of lakes and rivers; earlier occurrence of spring events such as leaf-unfolding, bird migration and egg-laying; and shifts in the ranges in which plant and animal species are found. However, while certain effects of regional climate changes on natural and human environments are emerging, the influence of adaptation measures and non-climatic drivers on the observed effects have been difficult to distinguish (IPCC, 2007c).

A growing recognition of the wide-ranging impacts of climate change has fueled efforts over the past several years to reduce greenhouse gas emissions. In 1991, the United Nations Framework Convention on Climate Change was adopted and ratified by 192 countries. This agreement established an overall framework for governments to gather and share relevant information, and launch mitigation and adaptation strategies. Its goal is to stabilize atmospheric concentrations of greenhouse gases at a level that will prevent dangerous interference with the climate system. In 1997, a substantial extension to the Convention was adopted in Kyoto, Japan. Known as the Kyoto Protocol, this treaty set legally binding emissions targets for industrialized countries, and created innovative mechanisms to assist these countries in meeting these targets. The Kyoto Protocol took effect on November 18, 2004, after 55 parties to the Convention had ratified it (U.N., 2008).

The United States has adopted a comprehensive strategy to reduce the greenhouse gas intensity (the ratio of greenhouse gas emissions to economic output) of its economy by 18 percent over the 10-year period from 2002 to 2012. U.S. climate policy relies on voluntary and incentive-based programs, along with multi-agency programs, to advance climate science and technologies (U.S. EPA, 2008b). One of the largest components of the U.S. climate change program is the Climate Change Science Program (CCSP), a multi-agency effort focused on improving our understanding of the science of climate change and its potential impacts. CCSP integrates federal research on climate and global change, as sponsored by thirteen federal agencies (U.S. EPA, 2008a).

In California, legislation passed in 1988 directed the California Energy Commission (CEC), in consultation with the Air Resources Board (ARB) and other agencies, to report on the State's greenhouse gas emissions and the how global warming might impact the State's energy needs, environment, agriculture, water supplies and economy

(California Climate Change Portal, 2008b). Senate Bill 1771 (Sher, Chapter 1018, Statutes of 2000) required that the CEC update the State's greenhouse gas emissions inventory by January 2002 and every five years thereafter. In 2006, with the passage of Assembly Bill 1803 (Committee on Budget, Chapter 77, Statutes of 2006), the responsibility for maintaining and updating this inventory was transferred to the ARB beginning in January 2007 (Health and Safety Code Section 39607.4).

California established the first comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective reductions of greenhouse gases with the enactment of the California Global Warming Solutions Act of 2006 (Nuñez, Chapter 488, Statutes of 2006) . Also known as AB 32, this law caps California's greenhouse gas emissions at 1990 levels by 2020. In addition, Governor Arnold Schwarzenegger has established a goal of reducing emissions to 80 percent below 1990 emission levels by 2050. Responsibility for monitoring greenhouse gas emissions and adopting plans and regulations to achieve emission reductions rests with the Air Resources Board.

During the 2007-2008 Legislative session, the California Legislature passed Senate Bill 375 (Steinberg, Chapter 728, Statutes of 2007), the first-in-the nation law to link greenhouse gas reduction to transportation and housing planning (http://www.leginfo.ca.gov/pub/07-08/bill/sen/sb_0351-0400/sb_375_bill_20080930_chaptered.html). In November 2008, Governor Schwarzenegger issued Executive Order S-13-08 to enhance the State's management of climate impacts from sea level rise, increased temperatures, shifting precipitation and extreme weather events (http://gov.ca.gov/executive-order/11036/). Coordination of state-level actions is carried out through a multi-agency Climate Action Team, led by the California Environmental Protection Agency (Cal/EPA) efforts (California Climate Change Portal, 2008a). To provide decision-makers and the scientific community with monitoring, analyses and scenarios on a broad range of topics relating to climate change and its impacts, the California Energy Commission continues to support research projects through its PIER Program.

USING ENVIRONMENTAL INDICATORS TO TRACK CLIMATE CHANGE

Environmental indicators are quantitative measurements and metrics that convey scientifically-based information on the status of, and trends in, environmentally related parameters. They facilitate the communication of environmental information to a broad audience by simplifying large volumes of complex environmental data into a concise, easily understood format, often using graphs and graphics.

Recognizing the value of environmental indicators, Cal/EPA initiated the EPIC Program in 2000, with the Office of Environmental Health Hazard Assessment (OEHHA) as lead. EPIC is intended to support the Agency's commitment to implement "results-based management," wherein information about environmental conditions – tracked using indicators – is considered as part of the program planning and evaluation processes. Working in collaboration with the Cal/EPA boards and departments, the Resources

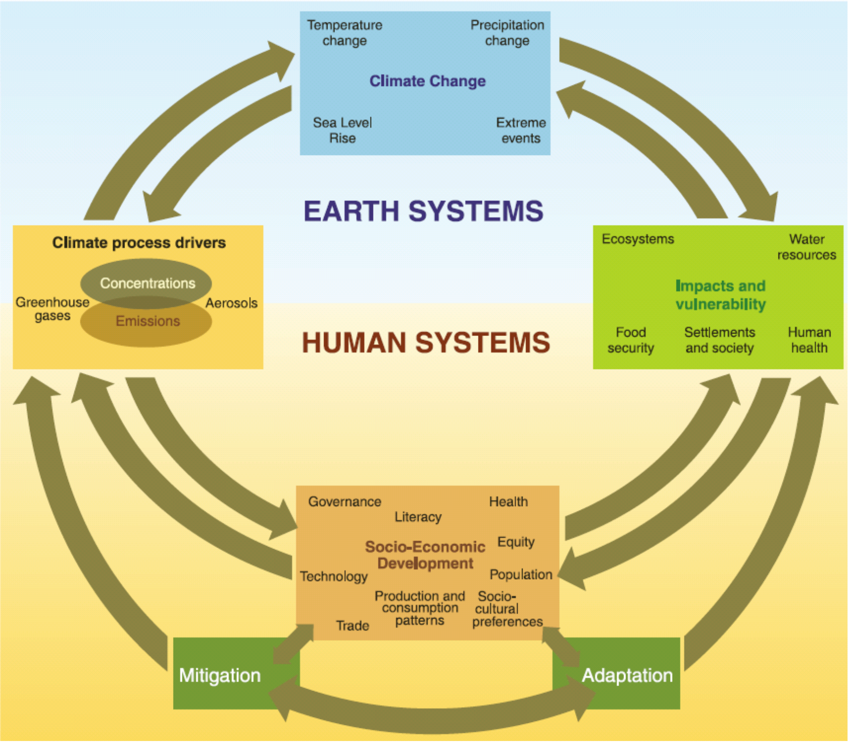
Agency, the Department of Health Services (now the Department of Public Health) and others, OEHHA adopted a framework and process for the selection and development of environmental indicators, and published an initial set of indicators in 2002. In 2003, the Legislature codified the EPIC Program by enacting Assembly Bill 1360 (Steinberg, Chapter 664, Statutes of 2003). This legislation mandates OEHHA to develop and maintain an environmental indicator system on behalf of Cal/EPA. The law further specifies the use of indicators by Cal/EPA and its boards and departments for reporting and program planning purposes, including their use in developing and supporting budget change proposals.

The indicators presented in this report – selected using the process adopted by EPIC – track and report on trends in climate change drivers, how California's climate is changing, and how these changes are impacting physical and biological systems. The indicators characterize the multiple facets of climate change in California, serving as tools for Cal/EPA in communicating technical data to the public in relatively simple terms. They can assist Cal/EPA and the ARB in evaluating the costs and benefits of regulatory action. Taken collectively, the indicators can help the research community (including the CEC's PIER Program) in examining the interrelationships between and among climate and other physical and biological elements of the environment, and in identifying gaps in information. Finally, the indicators can reveal evidence of the already discernable impacts of climate change, highlighting the urgency for the state to undertake mitigation and adaptation strategies.

Indicator selection

Following the EPIC process, the first step in indicator development involves the identification of the issues to be addressed by the indicators. The issues relating to climate change in California consist of: human-induced or anthropogenic drivers of climate change; changes in climate; and impacts of these changes on physical or biological systems.

These three issues are captured in the boxes labeled "climate process drivers," "climate change," and "impacts and vulnerability" in Figure 2.



Source: IPCC, 2007b

Figure 2. Schematic framework representing anthropogenic drivers, impacts of and responses to climate change, and their linkages.

This schematic framework, developed by the IPCC, represents the linkages between climate change-related elements of natural and human systems. Socio-economic development, which encompasses societal responses that influence drivers as well as impacts of climate change, are beyond the scope of the current report.

To identify candidate indicators to characterize the issues, OEHHA reviewed relevant studies and publications. Sources reviewed include research studies funded by the California Energy Commission's Public Interest Energy Research (PIER) Program (CEC, 2008); the IPPC Fourth Assessment Reports; other relevant governmental publications; and peer-reviewed journals.

As specified in the selection criteria adopted for the EPIC Program, selected indicators must be derived from scientifically acceptable data that support sound conclusions about the system being studied. In addition, the indicators must closely represent the issue, be sufficiently sensitive to detect changes in the system, and provide meaningful basis for decision-making. In addition to the new indicators identified in this process, the climate change indicators from the 2002 EPIC Report are also updated.

Classification based on data availability

Selected indicators are classified into three categories based on the availability of data for presenting a status or trend for the issue it represents, as follows:

> ***Type I***: Adequate data are available and can be used to support the development of the indicator. These data are generated by ongoing, systematic monitoring or data collection efforts.
>
> ***Type II***: Full or partial data generated by ongoing, systematic monitoring and/or collection are available, but either a complete cycle of data has not been collected, or further data analysis or management is needed in order to present a status or trend.
>
> ***Type III***: No ongoing monitoring or data collection is in place to provide data for these indicators. At the present time, these indicators are conceptual or have not been developed beyond one-time studies that provide only a snapshot in time. Type III indicators represent data gaps.

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INDICATORS OF CLIMATE CHANGE[*]

CLIMATE CHANGE DRIVERS

- Greenhouse gas emissions
- Atmospheric carbon dioxide concentrations

CHANGES IN CLIMATE

- Temperature
  - Annual air temperature: Statewide and Regional
  - Air temperature: By county population
  - Extreme heat events
  - Accumulated winter chill hours
- Precipitation
  - Annual precipitation: Statewide and Regional

IMPACTS OF CLIMATE CHANGE

- Impacts on physical systems
  - Annual Sierra Nevada snowmelt runoff
  - Snow-water content
  - Glacier change
  - Sea level rise
  - Lake Tahoe water temperature
  - Delta water temperature
  - Ocean temperature
  - Oxygen concentrations in the California Current

- Impacts on biological systems
  - *Impacts on humans*
    - Mosquito-borne diseases *(Type II)*
    - Heat-related mortality and morbidity *(Type III)*

  - *Impacts on vegetation*
    - Tree mortality
    - Large wildfires
    - Forest vegetation patterns
    - Alpine and subalpine plant changes (GLORIA) *(Type II)*
    - Wine grape bloom *(Type II)*

  - *Impacts on animals*
    - Migrating bird arrivals
    - Small mammal migration (Grinnell resurvey)
    - Spring flight of Central Valley butterflies
    - Copepod populations
    - Cassin's auklet populations

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[*] Unless otherwise noted, environmental indicators listed are classified as "Type I" (see page 6 for a description of the classification of indicators based on data availability).

BACKGROUND INDICATORS

Background indicators provide a context with which to interpret the meaning of environmental indicators. These indicators track trends in demographic, economic and other socio-economic factors that may directly or indirectly impact environmental conditions and resources in California.

The indicators presented in the document are those most relevant to understanding the climate change indicators which are the subject of this report. The full set of background indicators adopted by the EPIC Program can be found at: http://www.oehha.ca.gov/multimedia/epic/2002reptpdf/Chapter3background.pdf

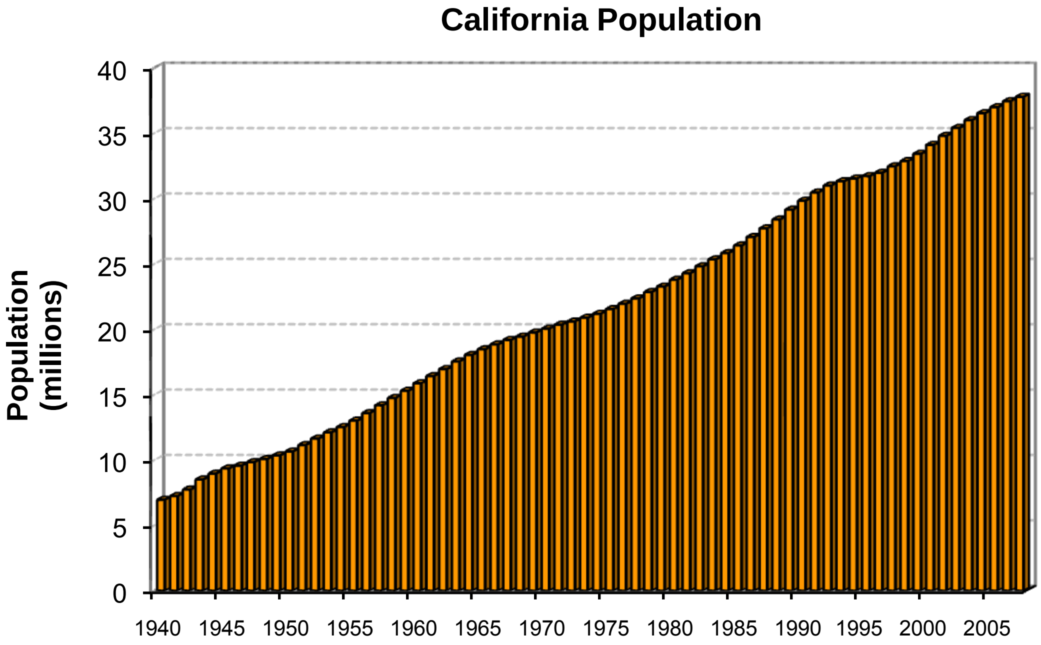
BACKGROUND INDICATORS

- Population
- Economy
- Energy consumption
- Transportation
- Land cover

Background indicators

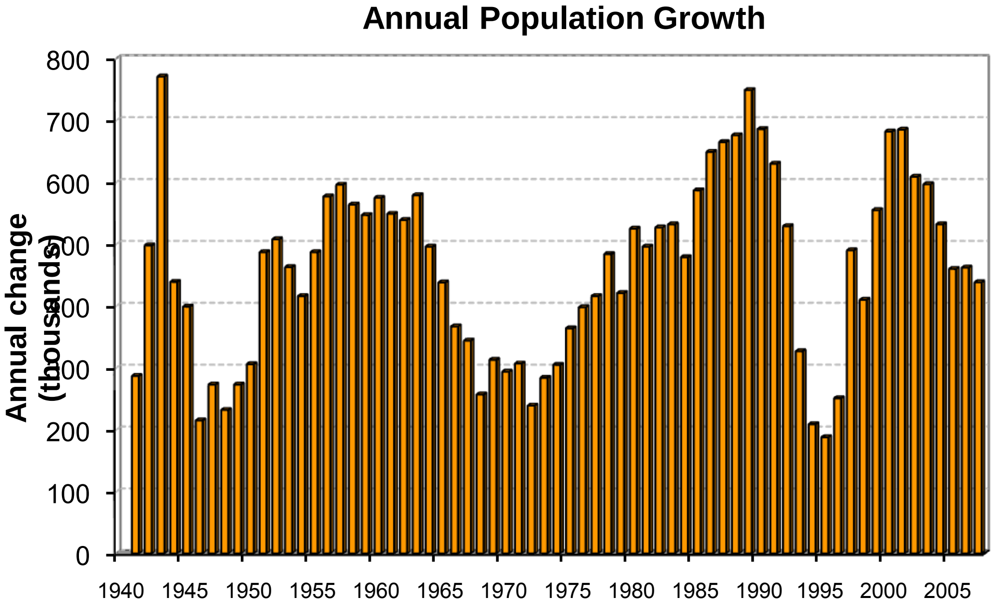
POPULATION

California continues to be the most populous state in the country, with a population that is 1.5 times more than that of Texas, the second most populous state. The State has an estimated 38 million residents as of 2007.



Source: DOF, 2007b; U.S. Census Bureau, 2007

The State's population growth in the past year was about 1.17 percent, representing 438,000 new residents. This continues the pattern of slower growth rates each year since the 2.0 percent growth in 2000.



Source: DOF, 2007a ; U.S. Census Bureau, 2007

Net migration contributed over 111,000 new residents, or 25 percent of the growth in the past year. Natural increase – that is, the balance of births and deaths – accounted for the rest of the growth (75 percent, 327,000 additional persons).

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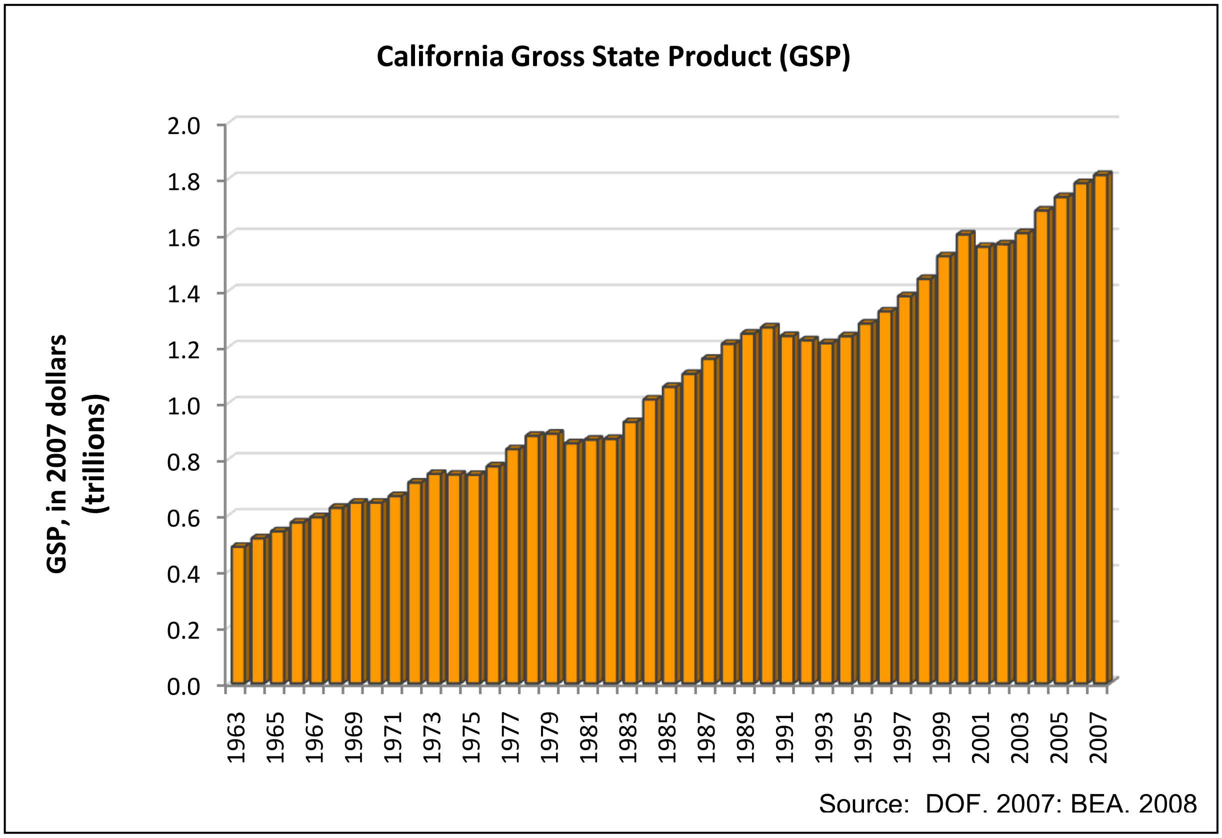
Background indicators

ECONOMY

In 2007, California's gross state product (GSP) -- the market value of the goods and services produced by labor and property -- was estimated to be over $1.8 trillion, accounting for approximately 13 percent of the nation's output. By comparison, the next largest state economy, Texas, makes up about 8 percent of the national economy, and is about 60 percent of California's. California's economy ranks among the world's top ten in 2007.

California's economy continued to grow through 2007, although at a slower rate. The State's economy had been growing at a rate faster than the nation since 2003. Between 2006 and 2007, this growth slowed dramatically and fell to 1.5 percent, lower than the national rate of 2.0 percent. According to the State Department of Finance, little growth is projected in 2008, followed by slow growth in 2009 and moderate growth in 2010. Sluggish home sales, falling home prices, tight credit conditions, dysfunctional financial markets and soaring food and energy prices have all had negative impacts on the State's economy. (DOF, 2008)



Source: DOF. 2007: BEA. 2008

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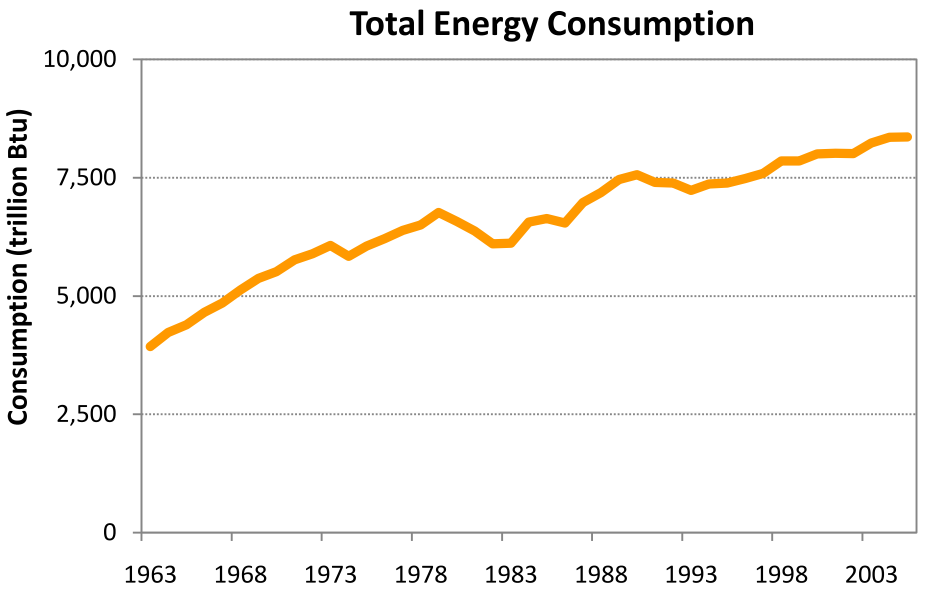
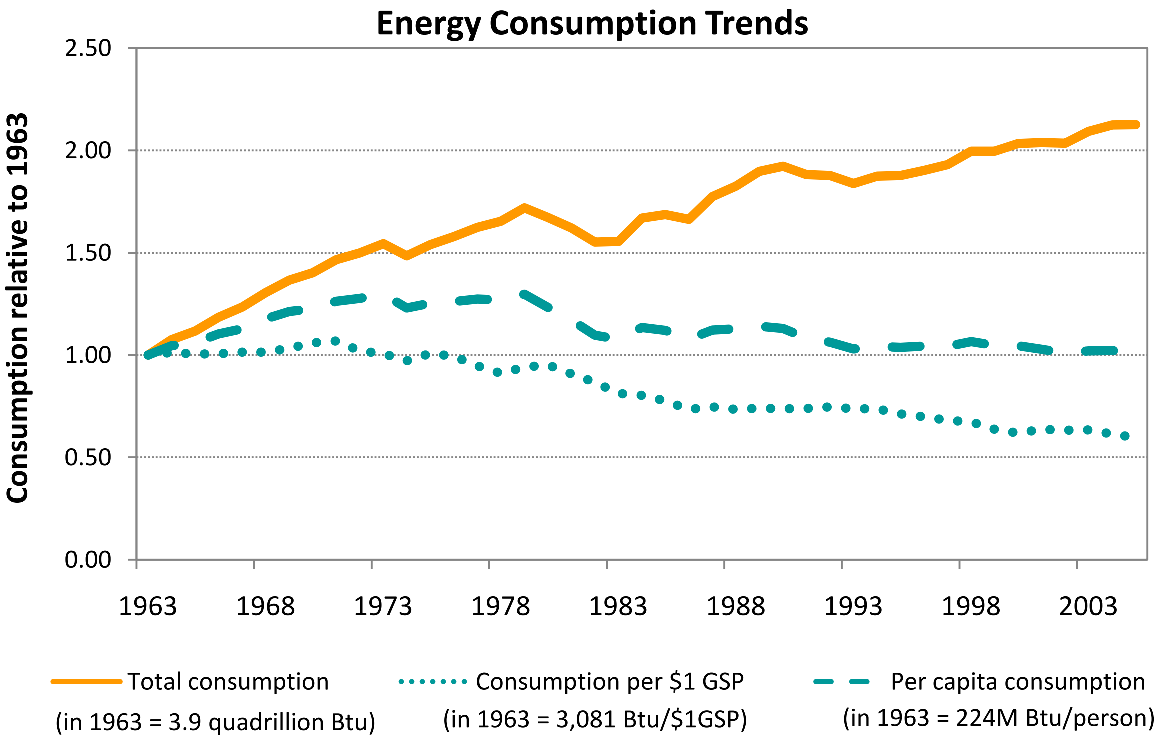
Background indicators

ENERGY CONSUMPTION

With a growing population and economy, total energy consumption in California continues to increase. However, energy consumed per unit of economic output (often called "energy intensity") continues to decline, as has per capita energy consumption.

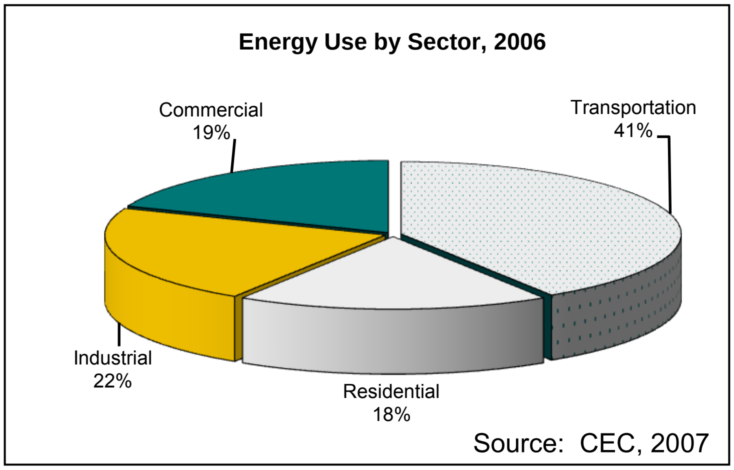


Source: DOF, 2007; BEA, 2008; EIA, 2008b

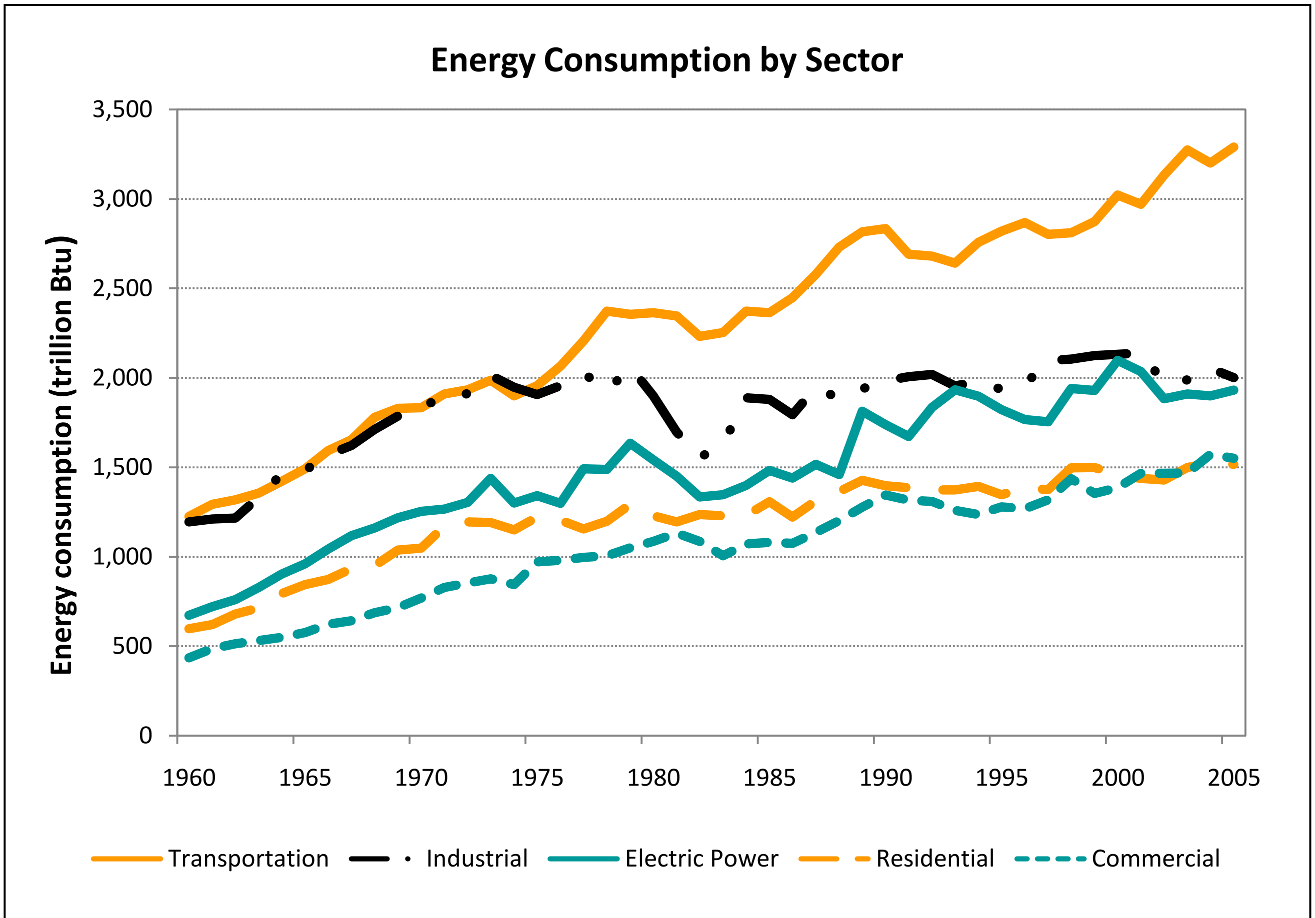


Source: EIA, 2008b; U.S. Census Bureau, 2008

The transportation sector continues to be the largest consumer of energy in California. More than 40 percent of all energy consumed in the state is used for transportation; almost all of this energy is derived from petroleum. The industrial, commercial, and residential sectors each account for about 20 percent of the state's energy consumption. (CEC, 2007)

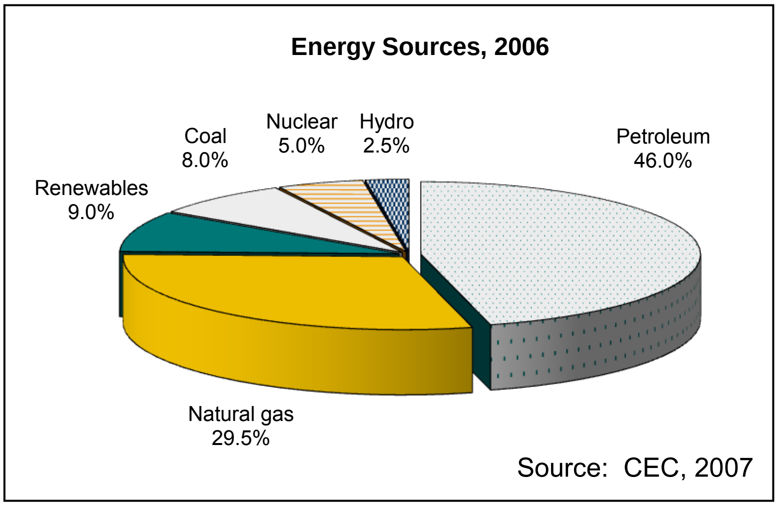


Source: CEC, 2007



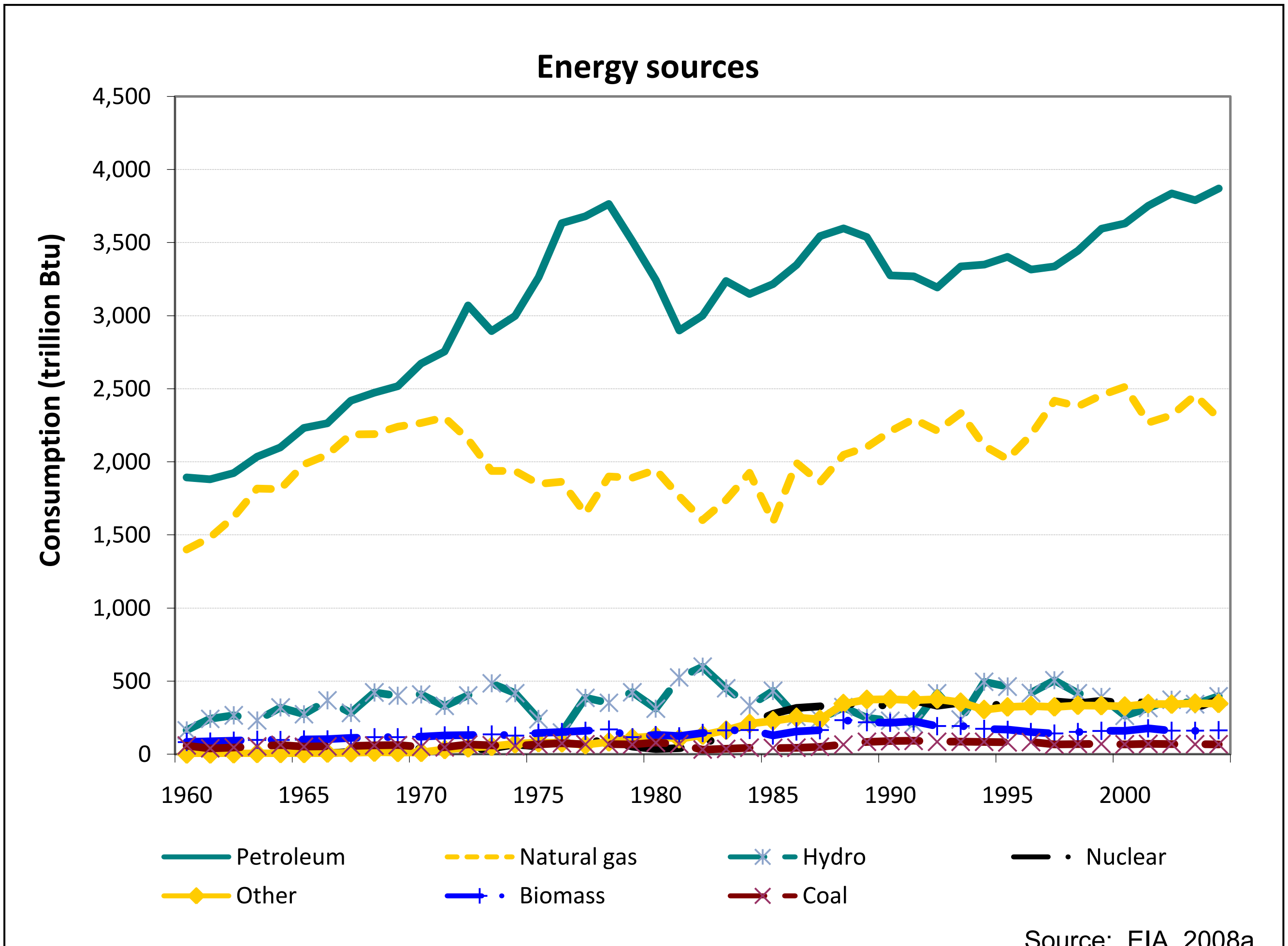
Source: EIA, 2008b

Petroleum makes up almost half of all fuel consumption in the State, and is primarily used for transportation. In 2006, Californians used almost 16 billion gallons of gasoline, making it the third largest consumer in the world, behind the entire United States and Canada. Natural gas, used for generating electricity and for heating, makes up almost one-third of the State's energy consumption. (CEC, 2007)



Source: CEC, 2007

The State has adopted a Renewables Portfolio Standard with a mandate of generating, by 2010, 20 percent of its electricity from renewable sources like biomass, geothermal, small hydro, solar, and wind.



Source: EIA, 2008a

References:

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EIA. (2008b). *State Energy Data Systems: California (Tables 8 to 11)*. U.S. Department of Energy, Energy Information Administration. http://www.eia.doe.gov/emeu/states/state.html?q_state_a=ca&q_state=CALIFORNIA .

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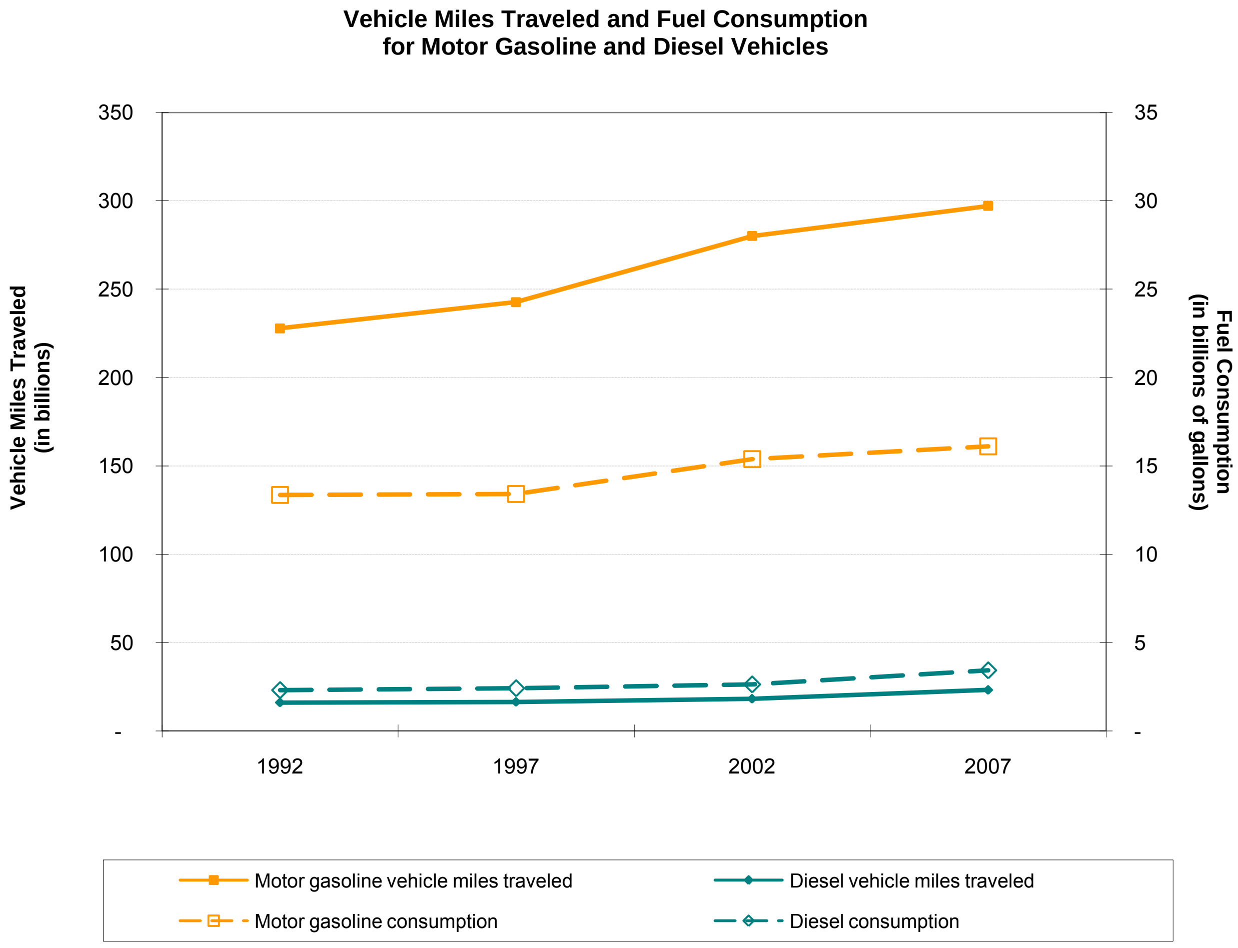
Background indicators

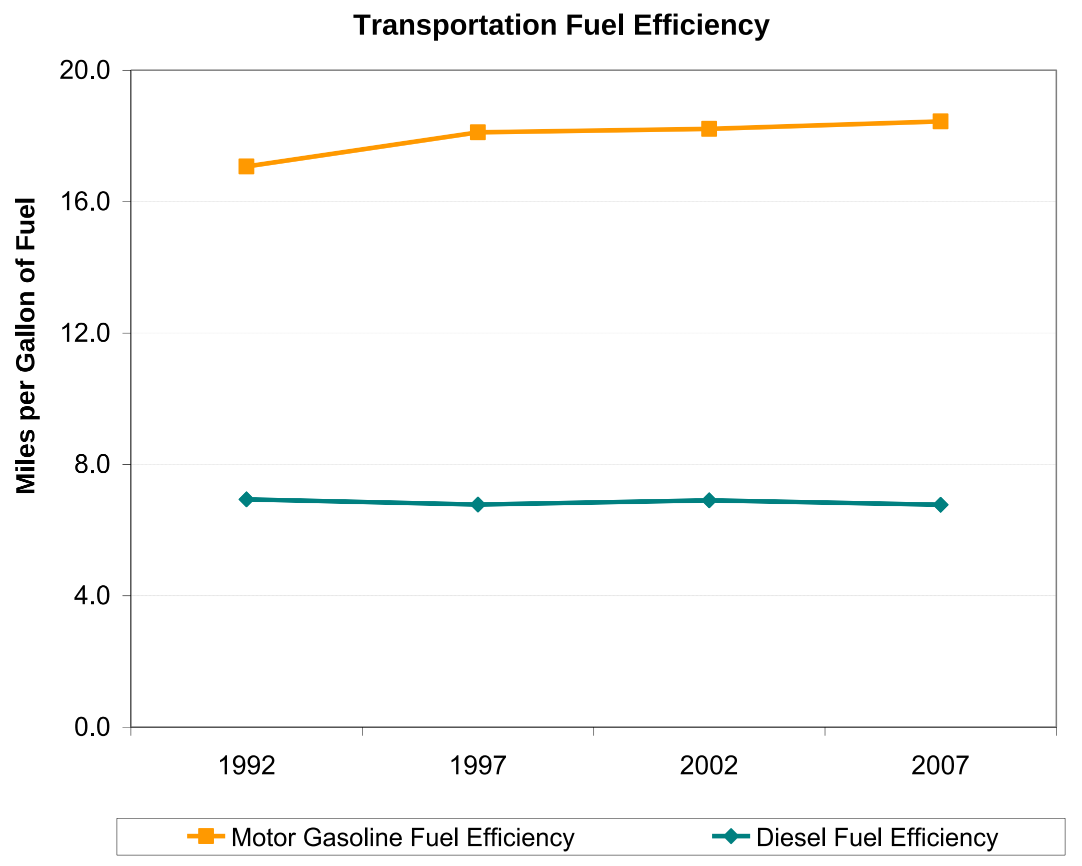
TRANSPORTATION

The number of vehicle miles traveled (VMT) and the volume of fuel consumed by motor gasoline vehicles continue to increase; in 2007, it is estimated that gasoline vehicles were driven almost 300 billion miles in the State, consuming an estimated 16 billion gallons of gasoline. By contrast, trends in VMT and fuel consumption for diesel vehicles have remained relatively unchanged over the past 15 years.



Source: CARB, 2006

Based on the above estimates of VMT and fuel consumption by the State's vehicle fleet, the average fuel efficiency estimated for diesel vehicles currently driven on California's roads in 2007 is 6.8 miles per gallon. The fuel efficiency trend for the diesel fleet has been largely unchanged since 1992. For motor gasoline vehicles, on the other hand, estimated fuel efficiency has improved from 17.1 miles per gallon in 1992 to 18.4 miles per gallon in 2007.



Source: CARB, 2006

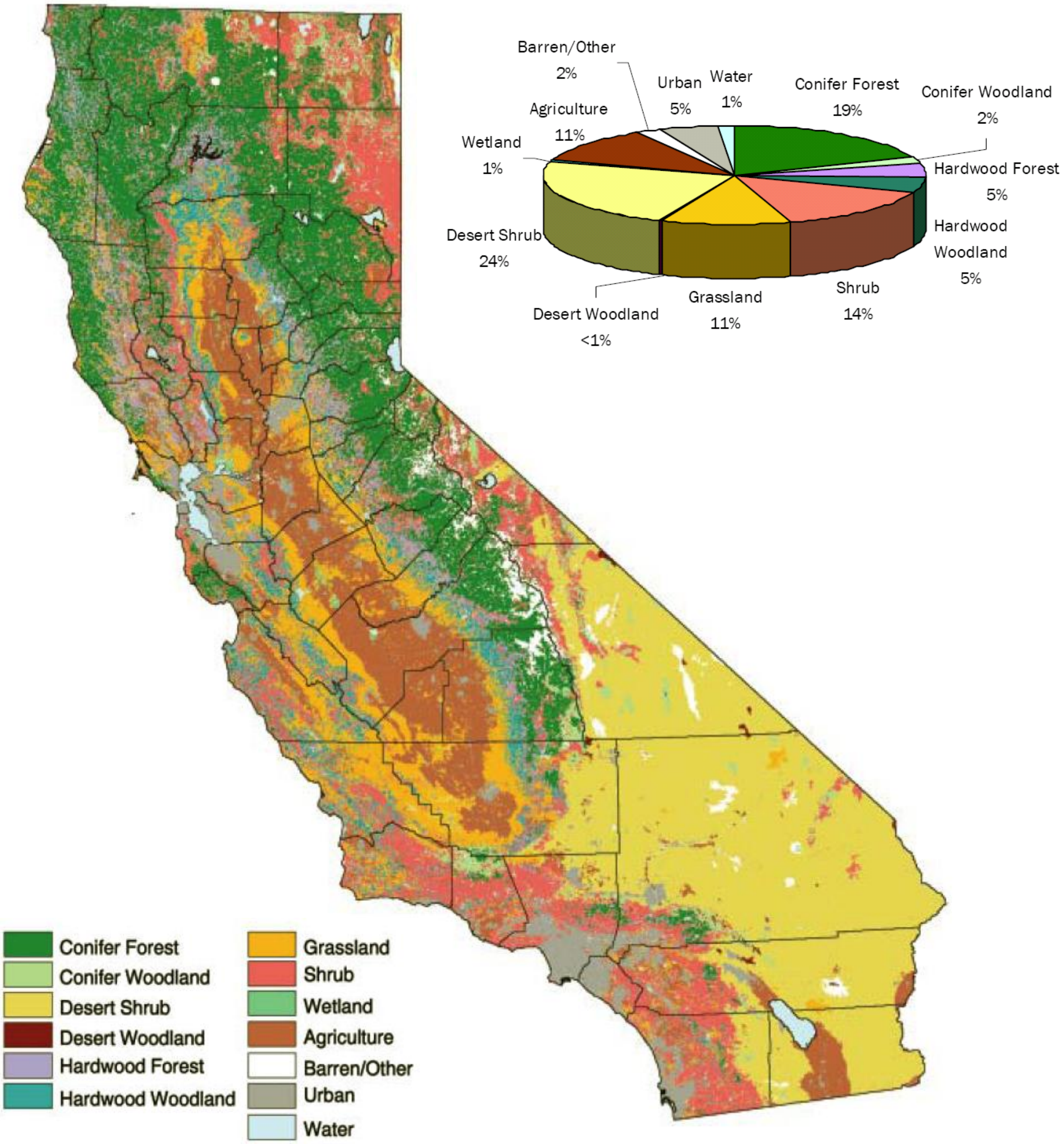
References:

CARB. (2006). *On-Road Motor Vehicle Inventory, EMFAC 2007 v 2.3 (Inventory includes all on-road vehicles, from light-duty passenger cars to heavy-duty trucks)*. California Air Resources Board. http://www.arb.ca.gov/msei/msei.htm .

Background indicators

LAND COVER

California's over 100 million acres of landscape consists predominantly of forests and rangelands, which includes the following categories shown on the map below: conifer forest, conifer woodland, desert shrub, desert woodland, hardwood forest, hardwood woodland, grassland, shrub and wetland. These make up about 80 percent of the State's area. Agricultural lands comprise about 11 percent of the State, and urban lands, about 5 percent.



Source: FRAP, 2003

The data presented are from the Forest and Range 2003 Assessment (FRAP, 2003). For purposes of this assessment, the following definitions apply: Forests are defined as lands with greater than 10 percent tree cover, and include the conifer forest, conifer woodland, hardwood forest and hardwood woodland land cover classes. Barren lands, those without any vegetation, are primarily those above the tree line. Water includes lakes, reservoirs, rivers and streams.

In addition to atmospheric concentrations of greenhouse gases, changes in land cover is an important human-induced factor affecting climate change and variability. Land use (e.g., residential, commercial, industrial, open space, and other designations) will determine land cover, and both are linked in complex and interactive ways to global climate change. Changes in land use and land cover influence climate; climate variability and change, in turn, can affect the land cover of a given area and the ways in which land can ultimately be used. (Climate Change Science Program, 2003)

Land cover influences biological, physical, chemical and energy exchange processes that affect climate at local, regional, and global scales. These processes include photosynthesis, respiration, decomposition, nitrification (and denitrification), and combustion. (Intergovernmental Panel on Climate Change (IPCC), 2006; IPCC, 2007a) In addition to impacts on the uptake and release of greenhouse gases, changes in land cover modify the amount of sunlight reflected back to space from the earth's surface (National Academies, 2008). Certain changes can modify evaporative cooling over a land area, leading to large alterations in surface temperature, both locally and regionally. Physical modifications to the landscape from urban development and agriculture replace vegetation with impervious surfaces such as roads, or conversion of dry surfaces into vegetated surfaces by irrigation. These alterations affect the distribution and retention of heat and moisture. (IPCC, 2007b)

Since the industrial era, human activities have altered the nature of land cover over the globe, principally through changes in croplands, pastures and forests. In addition, soot particles generated by human activities have modified the reflective properties of ice and snow. The likely net result of these changes is that more solar radiation is now being reflected from the earth's surface, producing a cooling effect. This effect, however, is relatively small compared to the warming associated with the increase in atmospheric greenhouse gases (IPCC, 2007a)

References:

Climate Change Science Program (CCSP). (2003). *Strategic Plan for the U.S. Climate Change Science Program. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research*. http://www.climatescience.gov/Library/stratplan2003/final/ccspstratplan2003-all.pdf.

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CLIMATE CHANGE DRIVERS

The Earth's climate is a complex, interactive system consisting of the atmosphere, land surface, snow and ice, oceans and other bodies of water, and living things. This system is influenced by its own internal dynamics, and by changes in external factors, both natural and human–induced. External factors that affect climate are called "forcings." Solar radiation and volcanic eruptions are natural forcings. Changes in atmospheric composition resulting from fossil fuel combustion are human-induced forcings (IPCC, 2007).

According to climate scientists, incoming energy from the sun and the reflection, absorption and emission of energy within the Earth's atmosphere and at the surface determine overall global climate. Changes in the atmosphere (such as in the concentrations of greenhouse gases and aerosols), land cover and solar radiation alter the energy balance of the climate system, and are drivers of climate change (IPCC, 2007).

INDICATORS: CLIMATE CHANGE DRIVERS[*]

Greenhouse gas emissions
Atmospheric carbon dioxide concentrations

References:

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. http://www.ipcc.ch/ipccreports/assessments-reports.htm .

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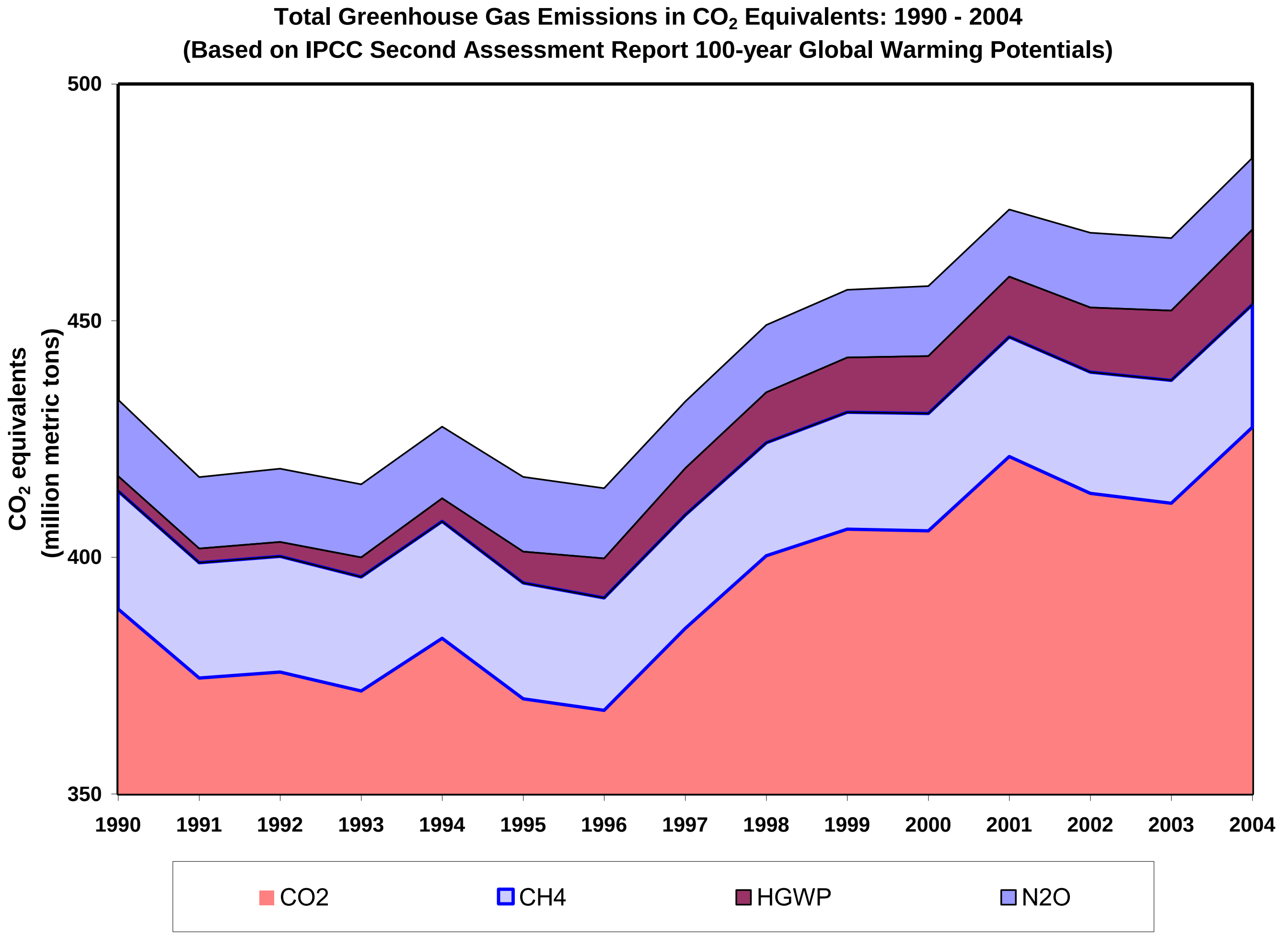
[*] Unless otherwise noted, environmental indicators listed are classified as "Type I" (see page 6 for a description of the classification of indicators based on data availability).

Climate change drivers

GREENHOUSE GAS EMISSIONS

Emissions have increased since 1990.

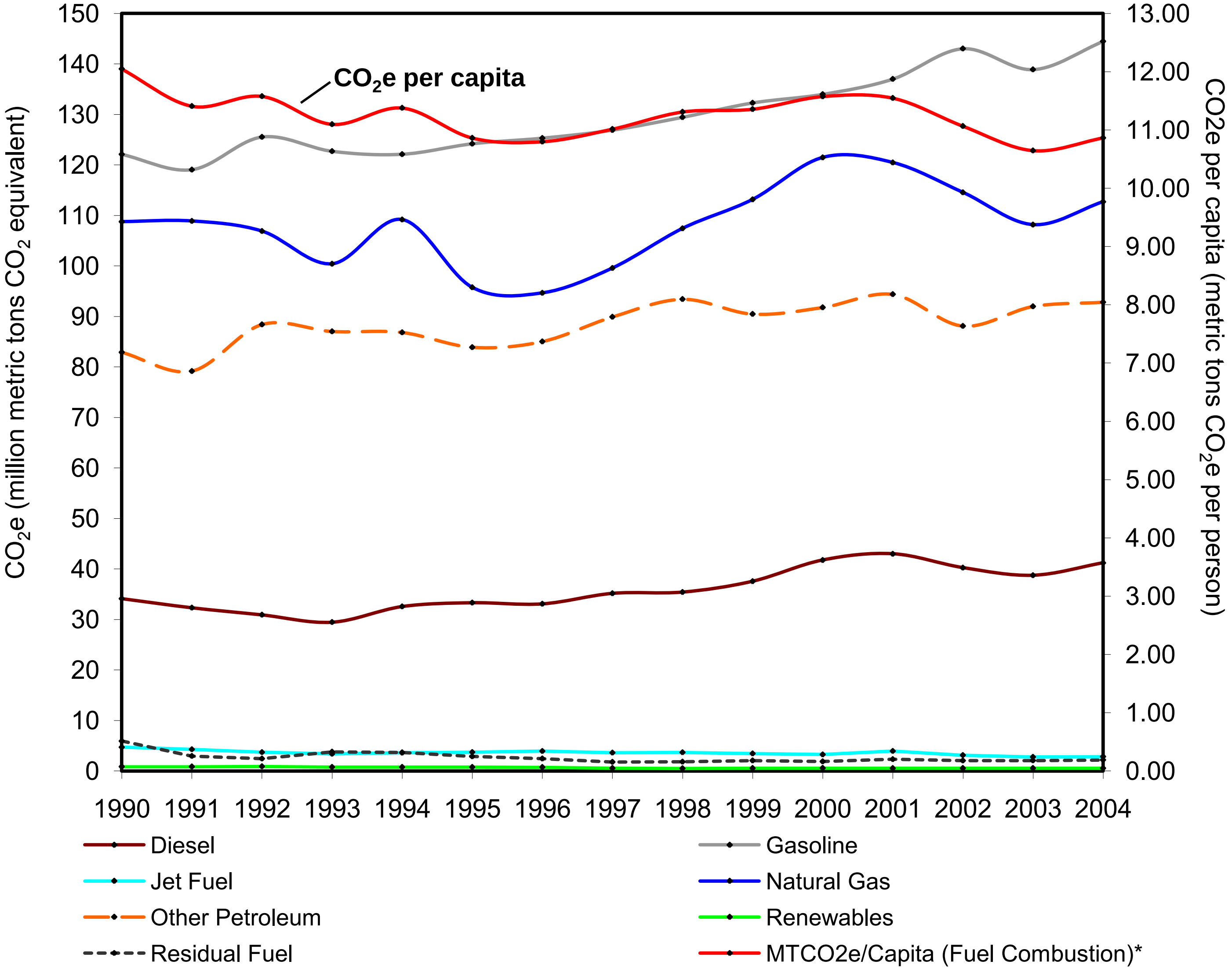


Source: ARB, 2008

What is the indicator showing?

Total California emissions of greenhouse gases (expressed in CO_2 equivalents) – including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and high global warming potential (HGWP) gases -- have increased between 1990 and 2004. Carbon dioxide equivalents are determined using “global warming potentials,” which are a quantified measure of the impact of different greenhouse gases on the atmosphere relative to that of CO_2. Greenhouse gases (GHG) are emitted from a variety of sources, most notably from the combustion of fossil fuels used in the industrial, commercial, residential, and transportation sectors. GHG are also emitted from landfills and from certain agricultural operations (ARB, 2008).

Total Emissions by Fuel Type: 1990 - 2004
(CO_2 Equivalents using IPCC SAR Global Warming Potential values)



Source: ARB, 2008

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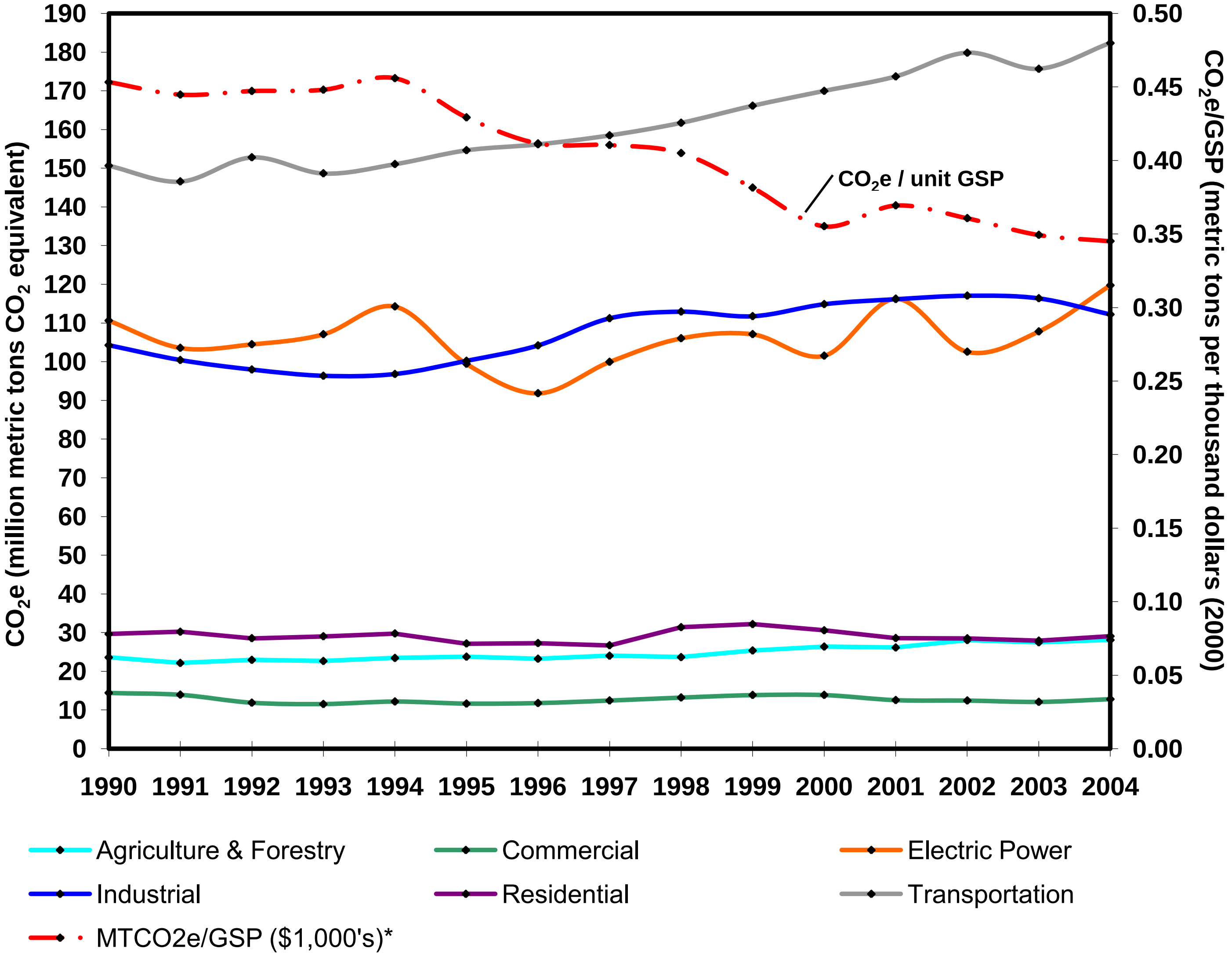
*MTCO2e = metric tons CO_2 equivalent

What is the indicator showing?

The contribution of GHG from the combustion of different fuels varies by fuel type. Non-renewable fossil fuels are used more than any other fuel type in California and emissions from the combustion of gasoline and natural gas have increased the most between 1990 and 2004. However, GHG emissions from fuel combustion on a per person basis have shown a slight decrease since 1990 while the State's population increased about 22 percent from 1990 to 2004 (ARB, 2008).

Total Emissions by Sector: 1990 - 2004
(CO_2 Equivalents using IPCC SAR Global Warming Potential Values)



Source: ARB, 2008

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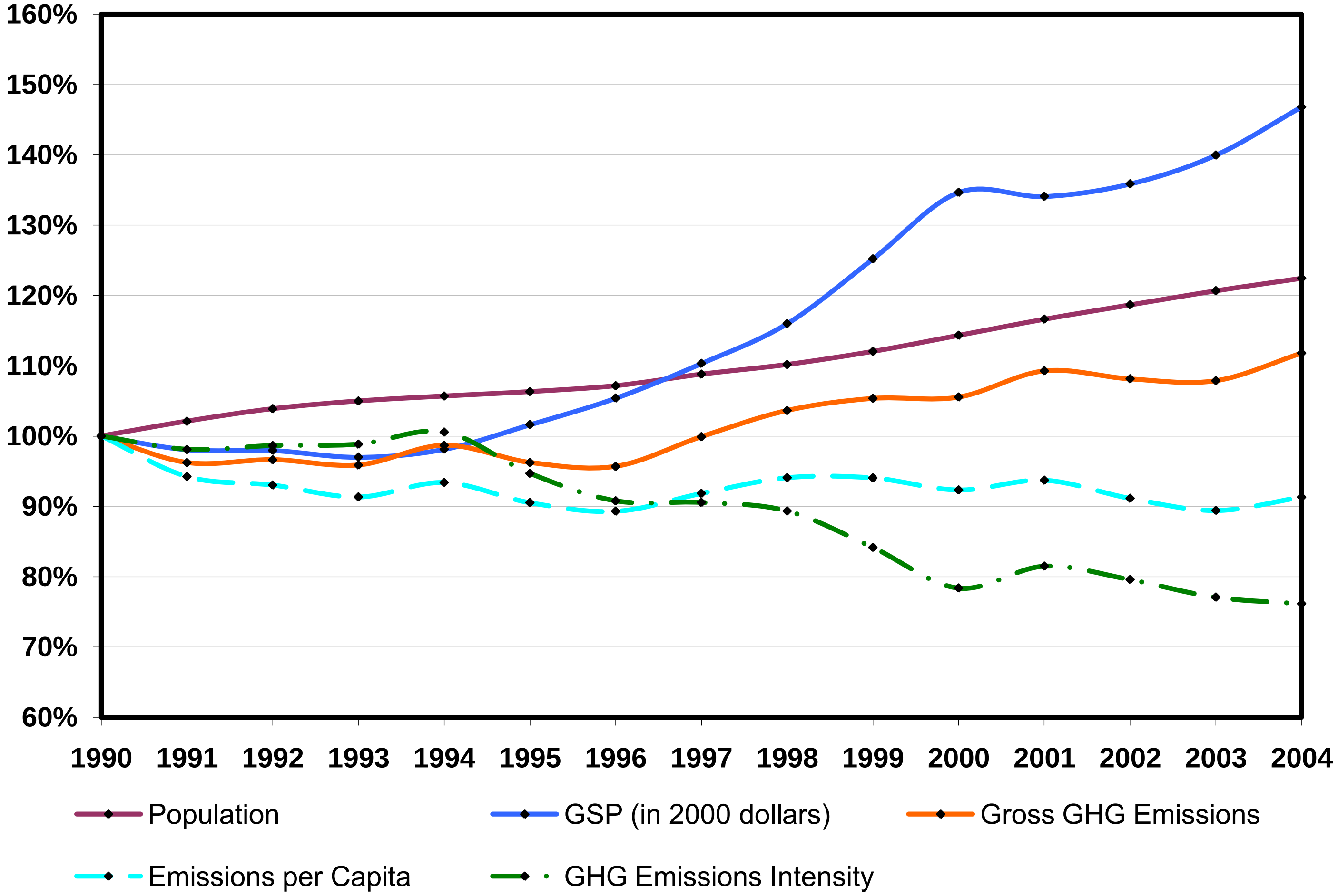
*MTCO2e = metric tons CO2 equivalent

What is the indicator showing?

Emissions of GHGs have increased for most of California's major economic sectors, with the most prominent increase in emissions occurring from transportation. The transportation sector includes emissions from on-road mobile sources, aviation, and shipping. The emissions of GHGs per unit of California's economic output, or gross state product (GSP), have decreased substantially between 1990 and 2004 (ARB, 2008).

Trends in California Population, Economy, Greenhouse Gas Emissions, Emissions per Capita and Emissions Intensity: 1990 - 2004 (Relative to 1990)

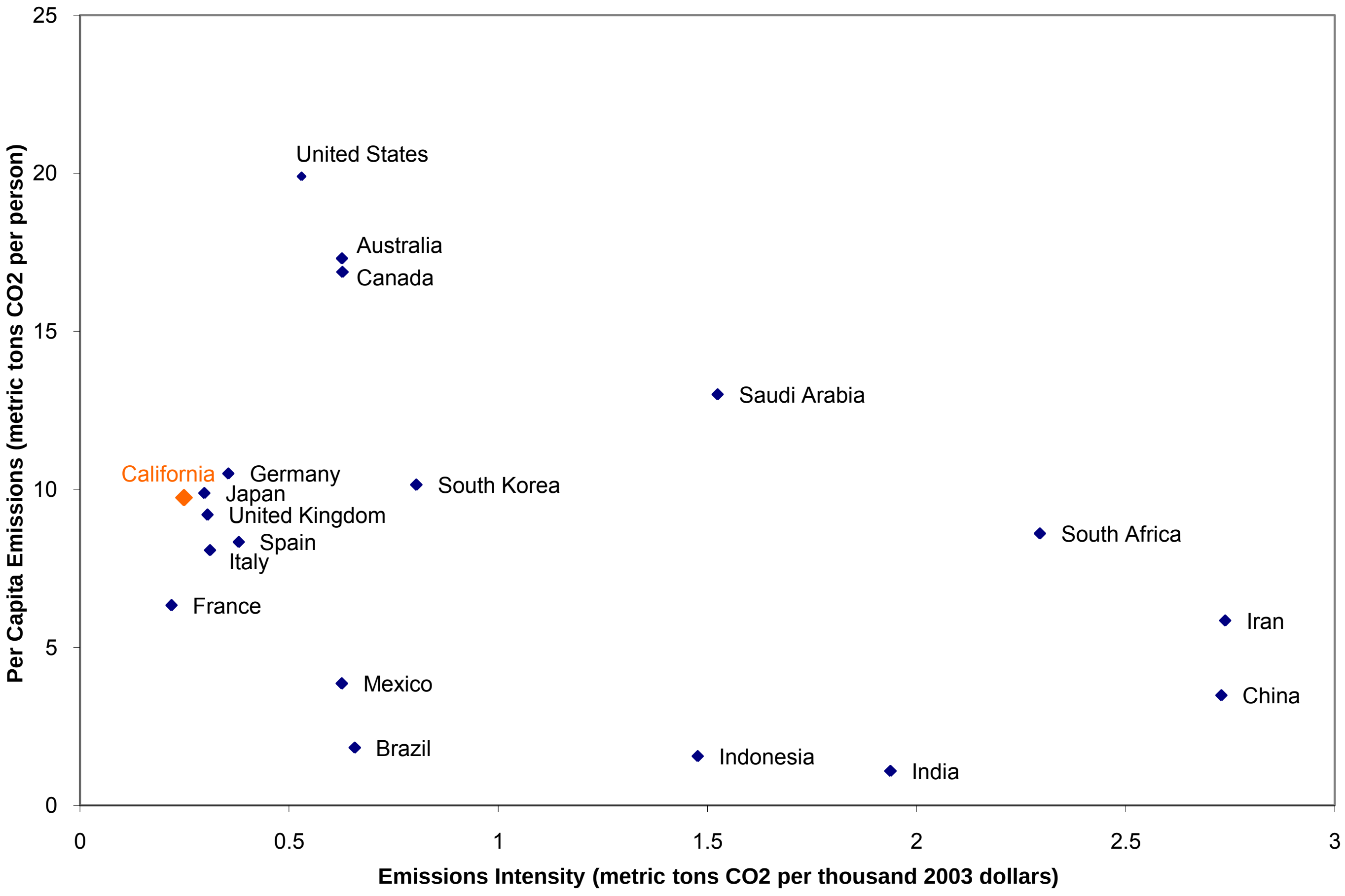


Source: ARB, 2008

What is the indicator showing?

Emissions on a per capita basis and per $1,000 of GSP, known as emissions intensity, have decreased from 1990 through 2004, even though the State's population and GSP have steadily increased by 22 percent and 47 percent, respectively (ARB, 2008).

Per Capita and CO2 Emissions Intensity in 2003



Data Sources: WRI, 2007; U.S. Census Bureau, 2007; United Nations, 2007; Bureau of Economic Analysis, 2007; and California Department of Finance, 2007

What is the indicator showing?

California's average per capita emissions of CO_2 and emissions intensity are lower than the average for the United States as well as most of the world's leading industrialized nations.

Why are these indicators important?

Atmospheric concentrations of GHGs have increased globally since the Industrial Revolution, enhancing the heat-trapping capacity of the earth's atmosphere (IPCC, 2007). Tracking trends in carbon dioxide (CO_2) emissions from fossil fuel combustion allows an assessment of California's contribution to global GHG emissions and climate change patterns. In addition, businesses which complete a GHG emissions inventory can use the indicator as a tool to better understand the processes which emit GHG, establish an emissions baseline, determine the carbon intensity ratio for an operation, and evaluate potential emission reduction strategies.

GHG compounds include CO_2, methane (CH_4), and nitrous oxide (N_2O), and high global warming potential (High GWP) gases. CO_2 emissions from the combustion of fossil fuels account for the largest proportion of GHG emissions. The Global Warming Potential (GWP) compares the radiative forcing of a GHG over a 100-year period to the reference value established for CO_2. (Radiative forcing is a measure of the degree by which a factor – such as a GHG – can alter the balance of incoming and outgoing energy in the earth-atmosphere system.) GWP values are used to convert non-CO_2 emissions to CO_2–equivalent units (CO_2e). High GWP gases include compound classes such as hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulfur hexafluoride (SF_6), nitrogen trifluorides (NF_3), and other halogenated chemicals.

In 2006, the California Legislature passed the Global Warming Solutions Act of 2006, which established an aggressive GHG emission reduction program to reduce emissions to 1990 levels. The California GHG Emission Inventory serves as a foundation for this program. The GHG inventory also provides a baseline for forecasting 2020 emissions to determine which emission levels will likely occur in the absence of additional policies and measures to reduce future emissions. The inventory provides regulatory staff with valuable information regarding a sector's emissions, sources, and processes. The GHG inventory is categorized by economic sector including Agriculture, Commercial, Electricity, Forestry, Industrial, Residential, and Transportation.

What factors influence these indicators?

Levels of CO_2 emissions are based on patterns of fossil fuel use, which in turn are influenced by a number of factors including population growth, Vehicle Miles Traveled (VMT), economic conditions, energy prices, consumer behavior and technological changes. For instance, improved economic conditions can result in an increased number of motor vehicles per household as well as higher VMT. More motor vehicles are registered in California than in any other state, and worker commute times are among the longest in the nation.

California's population has grown steadily from 1970 through 2004 which increases the demand for housing and transportation. More housing often means additional demand for residential energy with associated GHG emissions. Residential electricity use has increased in proportion to population growth, with a total increase of 24 percent from 1990 through 2004, while natural gas use in residences grew only slightly (CEC, 2006).

Unlike the trend in residential electricity, the overall increase in passenger vehicles was much higher than population growth, a 38 percent increase from 1990 to 2004 (ARB, 2007). The majority of current CO_2 emission sources in California are generated from transportation activities and electrical power generation. Much of the transportation-related growth in the late 1990s and early 2000s was in light duty trucks and sport utility vehicles, which consume more fuel (and emit more CO_2) than relatively fuel-efficient passenger cars.

Fossil fuel use in the state is further influenced by building and appliance standards for improved energy efficiency, by the availability of non-fossil fuel renewable energy alternatives, and by weather conditions. The dominant fuels combusted are natural gas (which is used primarily for in-state electricity generation and for residential and industrial uses) and gasoline consumption for transportation purposes. The per capita electricity consumption for California is the lowest in the nation which is primarily due to mandated energy efficiency programs (CEC, 2007). The declining trend in CO_2 emissions per GSP is an indication of higher energy efficiency over time, an increasing use of lower carbon fuels, and a transition to a more service-oriented economy. Further, because of the state's relatively mild weather conditions, California's heating-related fuel consumption tends to be lower than for other U.S. states.

Electricity Generation was the second highest emitting sector for 1990 through 2004, with an 8 percent increase in 2004 from the 1990 emissions level (ARB, 2007). Natural gas power plants account for approximately 50 percent of in-state electricity generation. Nuclear power plants supply 20 percent of the electrical generating capacity. Hydroelectric power generates approximately 20 percent of California power. Other renewable energy sources utilized in the state include wind, geothermal, solar, and waste products. Because of high electricity demand, more electricity is imported to California than in other states. A portion of the imports consist of power from coal fired energy plants. Coal power generation results in greater CO_2 emissions than that from other fuels used to produce electricity.

In the past, California has imported about one-third of its electricity from other states (CEC, 2006). To meet the state's electricity demand, more power plants are being constructed. Fossil fuel consumption from these new power plants may increase state CO_2 emissions. However, the new power units are required to be more efficient than many current power plants in operation and thereby produce less CO_2 emissions per unit of electricity generated.

Technical Considerations:

Data Characteristics

A GHG inventory is an estimate of the amount of GHG emitted to or removed over a specified area and time period from known sources or categories of sources. Carbon dioxide resulting from the combustion of fossil fuels account for the largest proportion of GHG emissions (88 percent of total GHG in 2004) and thereby CO_2 is considered a representative indicator of California's contribution to global concentrations of GHG. In comparison, CH_4 accounted for 5 percent of the state's total GHG emissions in 2004 while N_2O was approximately 3 percent (ARB, 2007).

The State's GHG inventory work was previously completed by the California Energy Commission (CEC). That responsibility was transferred to the California Air Resources Board (ARB) in 2006 at which time a GHG inventory was compiled for the years 1990 through 2004. ARB staff conducted a review and update of the existing CEC inventory, including the data sources and methods used for calculations. The ARB emissions inventory is California's official GHG inventory.

Inventories generally use one of two basic approaches to estimate emissions. The first is a top-down approach, which utilizes state, regional, or national level data. An example would be using statewide fuel use to estimate CO_2 emissions for a category of emission sources, such as petroleum refining. The second approach, bottom-up, relies on facility-specific data to estimate emissions from each source so that emissions for the category of sources are the sum of all facilities' emissions in the geographic area of interest. Calculation methodologies which are utilized include references such as the United Nations Intergovernmental Panel on Climate Change and the United States Environmental Protection Agency National Greenhouse Gas Inventory.

The California inventory is primarily a top-down inventory since it relies on statewide or regional data sources to estimate emissions at a state level of aggregation. Where data were available, staff used a bottom-up approach. Industry supplied information is also corroborated against federal and state data sources when available. Further research and data collection activities will be conducted in order to improve the accuracy and completeness of emissions data and calculation methods. Research is being performed by federal and state agencies as well as by academic institutions. Some areas of GHG inventory improvement being evaluated include studies on the effects of land use change and urban planning, improving building energy efficiency standards, evaluation of industrial manufacturing process efficiency measures, review of forestry management practices, survey of High GWP emission sources, evaluating a life cycle analysis for both fuels and agriculture, and the development of protocols for data collection and reporting.

ARB is conducting research projects on atmospheric concentrations of GHG pollutants. Ambient monitoring at Mount Wilson, within the South Coast Air Basin, consists of measurements of CH_4, carbon monoxide (CO), High GWP compounds, and Volatile Organic Compounds (VOC). The Mount Wilson study will also present an analysis of CH_4 to CO comparisons to determine differences between urban and rural pollutant concentration ratios. Ambient air sampling for GHG compounds is also being performed at the Walnut Grove, California tower south of Sacramento. Furthermore, aircraft and ocean vessel studies are being completed (in collaboration with the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and CEC) in order to obtain atmospheric GHG samples and data collection for ozone, cloud properties, aerosols, and black carbon. Ambient measurement data can augment information reported by facilities to ARB and lead to improved spatial resolution of GHG emissions.

Strengths and Limitations of the Data

The California GHG inventory includes emissions from all anthropogenic sources located within California's boundaries, as it is a statewide inventory. The inventory, however, excludes emissions that occur outside California during the manufacture and transport of products and services consumed within the state.

Pursuant to the California Global Warming Solutions Act of 2006, the electricity sector specifically includes GHG emissions from both in-state generated power and imported generation of electricity delivered to and consumed in California. Emissions from transmission line losses of electricity, as well as SF_6 emissions from transmission equipment, are also included in the state inventory and requires that ARB include imported electricity in the inventory, whereas the international and U.S. inventories do not (AB32, Global Warming Solutions Act of 2006).

The California inventory also contains emissions from in-state aviation and internationally-flagged ships within California waters provided that either their origin or destination is a California port.

The methods used to develop the California GHG inventory are consistent with international and national guidelines and protocols to the greatest extent possible. Emission factors are evaluated over time and efforts are being made by ARB to refine source specific emission factors from proposed sampling activities at sites such as landfills and composting operations, abandoned oil and gas wells, agriculture and other land use practices. Consistency maximizes the comparability of the inventory with inventories from other states and nations. This is important as California considers participation in standardized regional, national, and international GHG emission reduction programs.

References:

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For more information, contact:

Karen Lutter, P.E.
Air Resources Board
California Environmental Protection Agency
P.O. Box 2815
(916) 322-8620
klutter@arb.ca.gov

Climate change drivers

ATMOSPHERIC CARBON DIOXIDE

Concentrations of carbon dioxide in the atmosphere are increasing in California, consistent with global trends.

Monthly average atmospheric carbon dioxide concentrations

Sources: Keeling, et al., 2008a and b (La Jolla and Mauna Loa data); NOAA, 2008a (Point Arena and Trinidad Head data)

California carbon dioxide monitoring locations

Source: Lawrence Berkeley Laboratory, 2007

What is the indicator showing?

Atmospheric concentrations of the greenhouse gas carbon dioxide (CO_2) are increasing at coastal sites in California. Measurements at La Jolla, as well as shorter term measurements at Trinidad Head and Point Arena, are consistent with global trends, as represented by the measurements at Mauna Loa, Hawaii.

Why is this indicator important?

CO_2 is the most important anthropogenic greenhouse gas (GHG) in the atmosphere. It is responsible for 63 percent of the total radiative forcing caused by long lived GHGs (WMO, 2007). (Radiative forcing is a measure of the degree by which a factor – such as a GHG – can alter the balance of incoming and outgoing energy in the earth-atmosphere system.)

Because CO_2 is long-lived and well mixed in the atmosphere, measurements at remote sites provide an integrated picture of large parts of the Earth. Monitoring at Mauna Loa, Hawaii (located at 19^oN), which was started by Charles D. Keeling in 1958, provides the first and longest continuous measurements of global atmospheric CO_2 levels. These data documented for the first time that atmospheric CO_2 levels were increasing. In the 1980s and 1990s, it was recognized that greater coverage of CO_2 measurements over continental areas was required to provide the basis for estimating sources and sinks of atmospheric CO_2 over land as well as ocean regions.

High-precision measurements such as those presented in this indicator are essential to the understanding of the movement of carbon through its reservoirs – including the atmosphere, plants, soils, and oceans – via physical chemical and biological processes collectively known as the "carbon cycle" (IPCC, 2007a; CCSP, 2008). Tracking the movement and accumulation of carbon in these reservoirs provides information necessary for formulating mitigation strategies. Data on atmospheric CO_2 levels, in particular, are needed for projecting future climate change associated with various emission scenarios, and for establishing and revising emission reduction targets (IPCC, 2007b).

What factors influence this indicator?

The concentration of CO_2 in the atmosphere reflects the difference between the rates of emission of the gas and the rates of removal processes. CO_2 is continuously exchanged between land, the atmosphere and the ocean through physical, chemical and biological processes (IPCC, 2007b). Prior to 1750, the amount of CO_2 released by natural processes (e.g., respiration and decomposition) was almost exactly in balance with the amount absorbed by plants during photosynthesis and other "sinks." Since then, global atmospheric CO_2 concentrations have increased from relatively stable levels (between 260 and 280 parts per million (ppm)) to about 380 ppm in 2006 (WMO, 2007; Tans, 2008). This increase is primarily due to emissions from the combustion of fossil fuels, with additional contributions related to land use – particularly deforestation, biomass burning, and agricultural practices (IPCC, 2007b).

While more than half of emitted CO_2 is currently removed within a century, about 20 percent remains in the atmosphere for many millennia. Consequently, atmospheric CO_2 will continue to increase in the long term even if its emission is substantially reduced from present levels. It should be noted that, while increasing levels of atmospheric CO_2 are affecting the climate, changes in the climate are likewise affecting the processes that lead to CO_2 uptake from, and release into, the atmosphere (IPCC, 2007c).

Atmospheric CO_2 concentrations reflect regional, as well as seasonal and interannual influences. Due to its higher fossil fuel emissions, Northern Hemisphere CO_2 concentrations are higher than concentrations at the Southern Hemisphere. Seasonal variations are attributed to seasonal patterns of plant growth and decay. Interannual variations have been attributed to El Niño and La Niña climate conditions; generally, higher than average increases in CO_2 correspond to El Niño conditions, and below average increases to La Niña (IPCC, 2007b).

Technical Considerations:

Data Characteristics

The NOAA Earth System Research Laboratory's Carbon Cycle Cooperative Global Air Sampling Network operates the most extensive network of international air sampling sites, which collates measurements of atmospheric CO_2 from a global network of almost 50 surface sites (IPCC, 2008c). Point Arena and Trinidad Head are two of the sites. Air samples are collected weekly in glass flasks, and CO_2 is measured by a nondispersive infrared absorption technique. Monitoring at Point Arena started in January, 1999, and at Trinidad Head, in April, 2002. Measurements are highly accurate (to ~ 0.2 micromol/mol or ppm) and precise (~ 0.2 micromol/mol based on repeated analysis of the same air) (NOAA, 2008).

At the Scripps Institute of Oceanography (SIO) La Jolla Pier, replicate samples are collected at intervals of roughly one month, on average over the period of record, although sampling intervals have ranged from weekly to almost quarterly in a few early cases. The sampling has become more frequent and regular in recent years. The record from the Mauna Loa Observatory in Hawaii is based on CO_2 measured in samples collected roughly twice per month until 1981, and at roughly weekly intervals thereafter. Samples are collected in 5 liter evacuated glass flasks, which are returned to the SIO for CO_2 determinations using a nondispersive infrared gas analyzer (Keeling and Whorf, 2004).

Strengths and Limitations of the Data

The long-term record at La Jolla, particularly when compared with the longer-term data at Mauna Loa, present valuable time-series information for tracking CO_2, trends over the past half century. The data are useful for characterizing seasonal variations in CO_2 concentrations and differences from background air that is remote from emissions and removals.

Although the La Jolla Pier at SIO extends far out over the ocean, the site can receive some air currents polluted with urban CO_2 that has hooked down from offshore breezes coming from Los Angeles that mix with the oceanic and San Diego atmosphere. Likewise, the Point Arena monitor, although coastal, captures onshore CO_2. The Trinidad Head monitor sits on a peninsula jutting into the ocean with a tower, but air coming from the Pacific backs up on the nearby coastal range mountains and backflows to the site thus contaminating the measurements with onshore air CO_2 .

The Earth System Research Laboratory of the National Oceanic and Atmospheric Administration (NOAA/ESRL) began measurements of CO_2 from a network of tall towers (utilizing existing television, radio and cell phone towers as sampling platforms) in 1992 (NOAA 2008). In 2003, California began designing regional GHG detection systems in metropolitan areas for research purposes (CEC report #CEC-500-2005-123, 2005), and in 2007 became the first state in the United States to start gathering regional data in a continuous measurement program (Nature News, 2007). The CALGEM Project is a collaboration between Lawrence Berkeley National Laboratory, the California Energy Commission, and NOAA's Global Monitoring Division, with the goal of evaluating the feasibility of estimating regional greenhouse gas emissions within California, and to improve prospects for estimating GHG emissions at the national scale in support of the North American Carbon Program.

CALGEM initially focused measurements in two locations. First, the Sutro Tower site above San Francisco was chosen to observe both oceanic air and urban air. Second, the Walnut Grove site was chosen to observe air that is heavily influenced by the urban and rural areas. Both the Walnut Grove and Sutro tower are instrumented with automated flask sampling systems that provide daily measurements of a suite of GHGs, carbon isotopes, halocarbons and other compounds. Recent work at LBNL and UC Irvine suggests that atmosphere-biosphere model predictions of atmospheric fossil fuel CO_2 uptake by plants are consistent with radiocarbon measurements in annual grasses across California and that approximately half the fossil fuel CO_2 added to the atmosphere by California is blown out of the state's Southern border rather than directly East (Riley, 2008).

Initial results have shown that GHG mixing ratios at the Central Valley site are significantly elevated above those measured at oceanic sites, indicative of the strength of California GHG emissions. Current work is now underway to quantify the magnitude and spatial distribution of emissions necessary to produce the elevated mixing ratios.

There are plans eventually to monitor gases at additional locations using *in situ* and flask sampling of CO_2 and other atmospheric trace gases. These measurements are the beginning of a long term record of GHG concentrations representing California's contribution to global climate change. The analysis will provide an initial estimate of the current level of GHG emissions at the regional level, to enable California to estimate how well the AB 32 reduction programs are working to reduce CO_2 and other GHG emissions.

Recent work has also extended the GHG measurements higher into the atmosphere. Scientists from the U.S. Department of Energy's Lawrence Berkeley National Laboratory, NOAA, the University of California, the California Air Resources Board, and NASA deployed aircraft outfitted with atmospheric sampling devices in the summer of 2008 to measure greenhouse gases over California. These efforts provide additional data to quantify regional carbon exchange and hence contributions to atmospheric radiative forcing. Flights covered several important regions in California including the Los Angeles air basin, as well as the San Francisco Bay and Central Valley areas.

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For more information, contact:

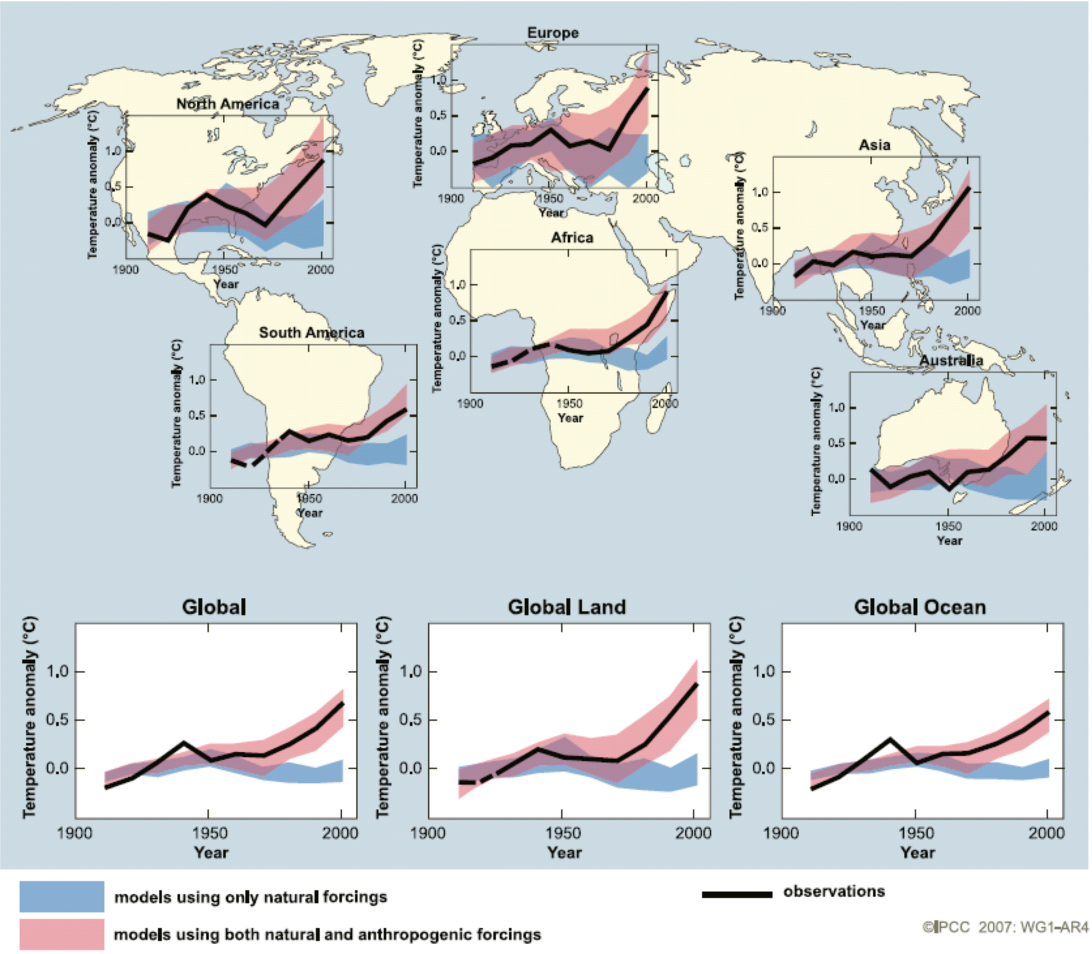
Marc Fischer
Atmospheric Science Department
Lawrence Berkeley National Laboratory
MS 90K-125
1 Cyclotron Road
Berkeley, CA 94720
(510) 486-5539
http://eetd.lbl.gov/env/mlf
MLFischer@lbl.gov

Pieter Tans
Earth System Research Laboratory
National Oceanic and Atmospheric Administration
325 Broadway
Boulder, CO 80303-3328
(303) 497-6678
Pieter.tans@noaa.gov

Guido Franco
California Energy Commission
1516 9th Street, MS-50
Sacramento, CA 95814
(916) 654-3940
gfranco@energy.ca.gov

CHANGES IN CLIMATE

Climate, which is generally defined as “average weather,” is usually described in terms of the mean and variability of temperature, precipitation and wind over a period of time. The IPCC concludes that globally, widespread observations of temperature increases and changes in other climate variables represent unequivocal evidence that the Earth’s climate is warming. While natural internal processes cause variations in global mean temperature for relatively short periods, the IPCC’s analysis found that a large portion of the observed temperature trend is due to external factors. As shown in the following figure, temperature trends observed over the past century more closely resemble simulations from models that include both natural and human factors, than those that incorporate only natural factors.



Source: IPCC, 2007

INDICATORS: CHANGES IN CLIMATE*

- Temperature
  - Annual air temperature: Statewide and Regional
  - Air temperature: By county population
  - Extreme heat events
  - Accumulated winter chill hours
- Precipitation
  - Annual precipitation: Statewide and Regional

Reference:

IPCC. (2007). *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf

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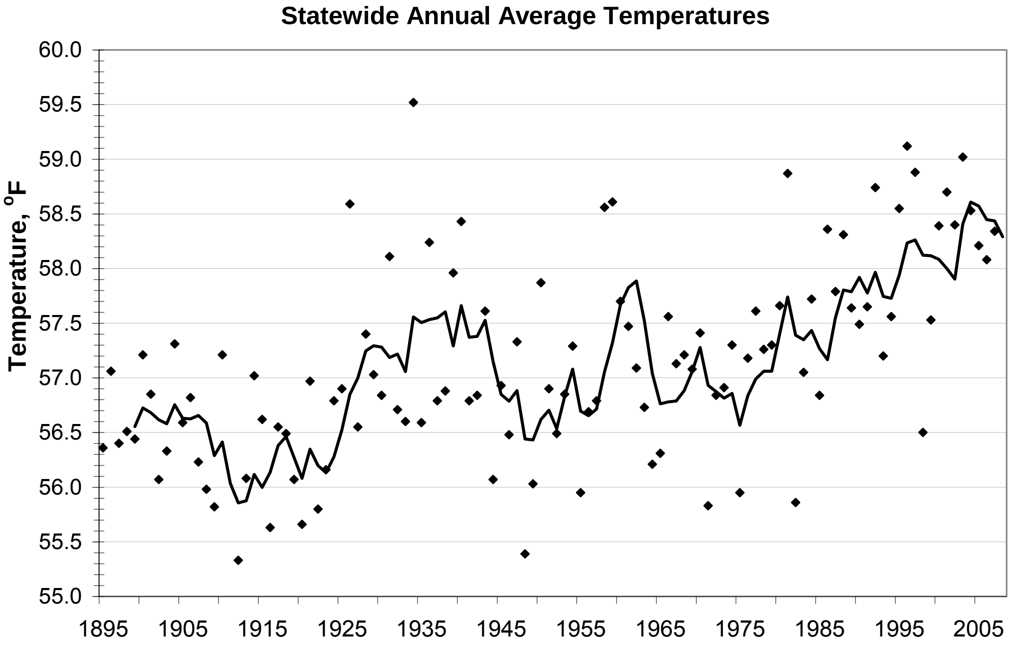
* Unless otherwise noted, environmental indicators listed are classified as "Type I" (see page 6 for a description of the classification of indicators based on data availability).

Changes in climate

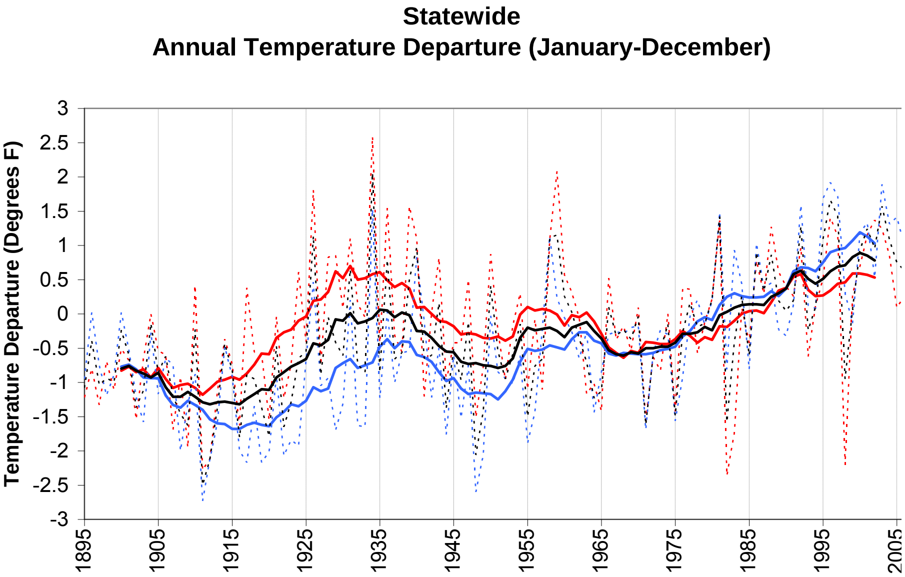
ANNUAL AIR TEMPERATURE

Air temperatures have increased over the past century.



Source: DRI, 2008

California annual average temperatures. Bold line is the 5-year running average.



Source: DRI, 2008

California annual (Jan-Dec) temperature, 1895-2007, expressed as departures from average. Red is maximum temperature, blue is minimum temperature, black is mean temperature. Bold lines are the 11-year running mean.

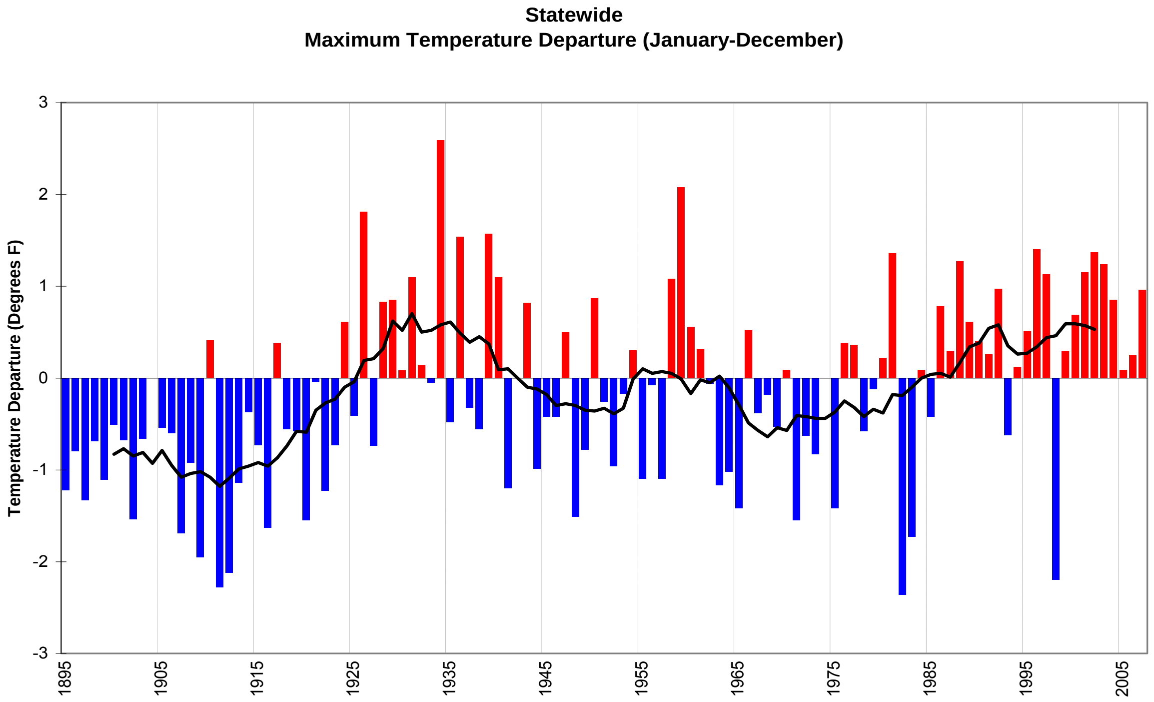
Definition of terms used

Average is the long-term average temperature based on data from 1948 to 2007.

Departure/anomaly describes the difference between the long-term average and the period of interest. For example, "annual temperature departure" is the difference between that year's average temperature and the long-term average. Positive values are above, and negative values are below, the long-term average.

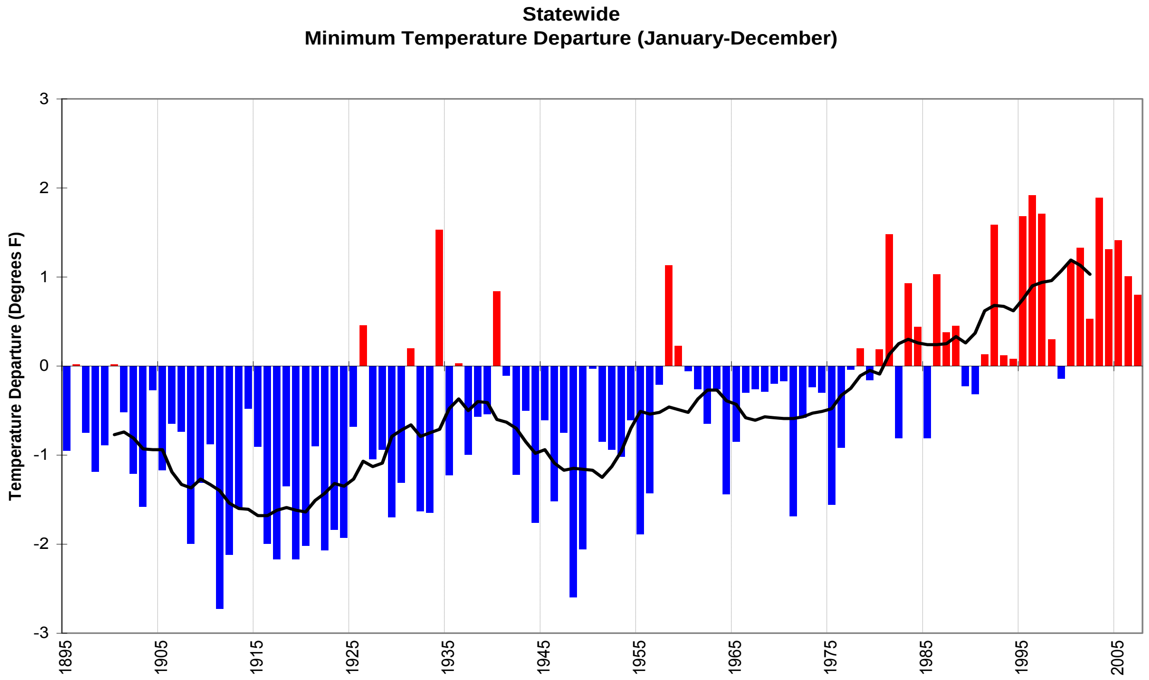
Maximum and minimum temperature as used here is often an average maximum or minimum temperature for a given length of time (i.e., a year, a season, or a month).

Mean temperature as used here is the simple average of maximum and minimum temperatures, or the sum of maximum + minimum, and divided by 2.



Source: DRI, 2008

California statewide annual (Jan-Dec) maximum temperature departure from long-term average. Red indicates above average annual temperature, and blue indicates below average. Bold line is the 11-year running mean.



Source: WRI, 2008

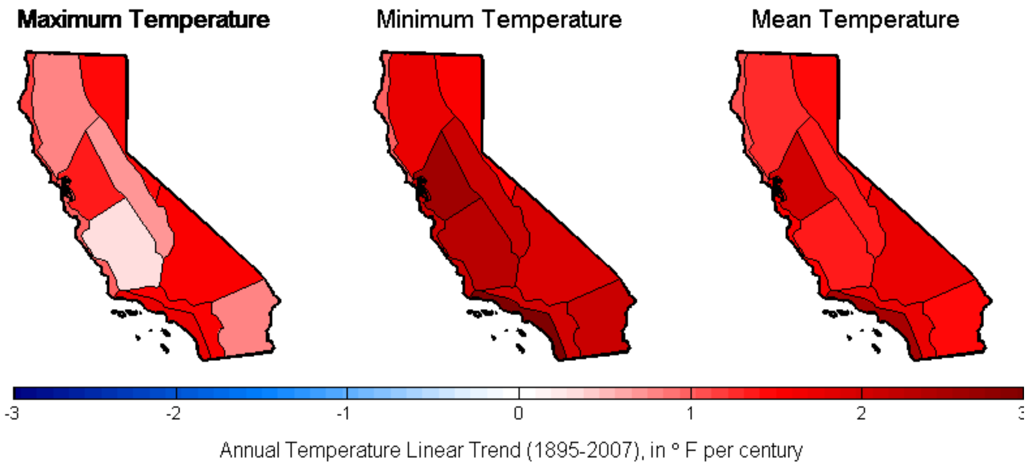
California statewide annual (Jan-Dec) minimum temperature departure from long-term average. Red indicates above average annual temperature, and blue indicates below average. Bold line is the 11-year running mean.

What is this indicator showing?
California Climate Tracker provides regional and statewide temperature trends. This operational database tracker for weather and climate monitoring information is updated with recent data monthly online at the Western Regional Climate Center at www.wrcc.dri.edu/monitor/cal-mon/index.html.

The statewide warming trend is consistent with that found globally in the most recent report published by the Intergovernmental Panel on Climate Change (IPCC, 2007). Maximum and minimum temperatures for California do not exhibit similar histories. Nighttime minimum temperatures have been increasing overall since the early 1900s. Daytime maximum temperatures, by contrast, have not increased greatly since the warm period in the 1930s. Day and night have shown temperature rises since the middle 1970s, the period of greatest global greenhouse gas forcing. Together, it appears that the increasing trend in mean California temperature is driven more by nighttime processes than by daytime processes.

The 11 climate regions within the state are showing the same warming trends over the last century. Clearly, the entire state has been warming in both minimum and mean temperatures, at approximately 2 degrees F per century. There are modest differences around the state in the rate of daytime warming.

Annual temperature trends per century for 11 climate regions in California



Source: DRI, 2008

Why is this indicator important?
Temperature is a basic physical element that affects many natural and human activities. Increasing temperatures will play an important part in California changes, for example, in agriculture, forestry, flooding, drought, economy, health, heat waves, extreme events, loss of species diversification and extinction, coastal flooding and erosion, and increased large forest fires.

What factors influence this indicator?

The factors that influence California temperature vary between day and night, among the seasons, and among geographic locations. The Pacific Ocean has a major effect all year along the coast, especially summer, and farther inland in winter. The prevailing winds from the west bring ocean moisture and temperature. However, climate patterns can vary widely from year to year and from decade to decade, in accordance with large-scale circulation changes around the Earth.

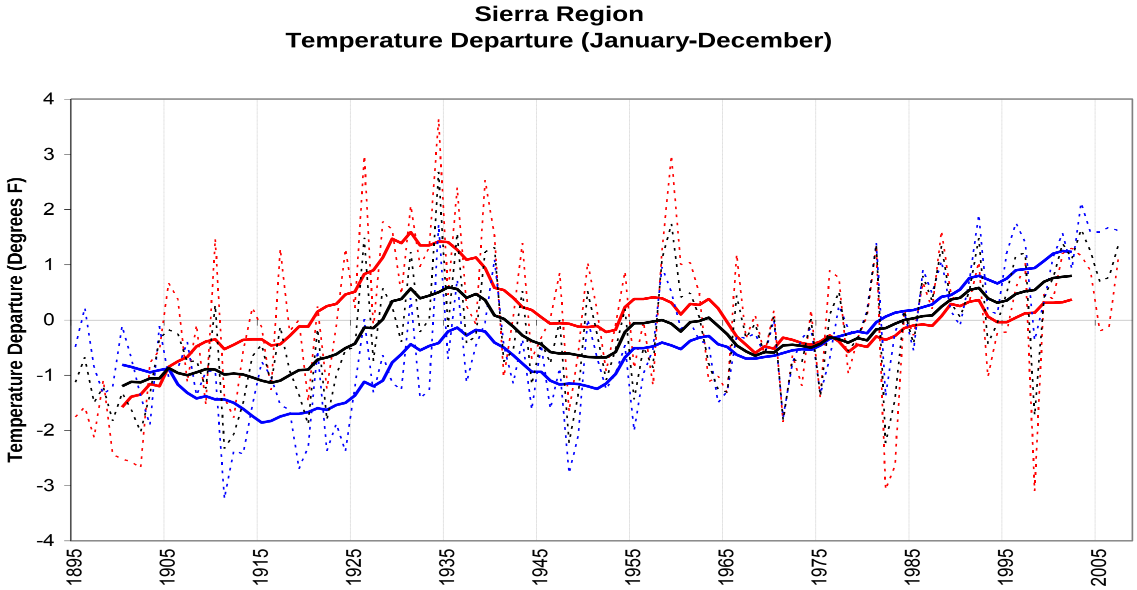
In the winter season, cold storm tracks extend from the Gulf of Alaska. Wetter, warmer storm tracks extend from the subtropical and tropical regions to the southwest. In summer, storm tracks retreat to the north, frontal systems are weaker, and drier weather prevails as the subtropical high over the Pacific dominates weather across the state. During summer local features such as ocean temperatures, land surface conditions and convective (thunderstorm) activity play a much stronger role.

There are local influences on temperatures as well, including land surface uses and types, for example, widespread irrigation, city urban heat island effects versus rural landscapes, and how those have changed over time. In addition, urbanization of historically rural areas can affect temperature, which is generally known to have a warming effect. There are also unequal warming trends in each season, and spring is of particular interest due to its apparent larger warming trend. Abatzoglou and Redmond (2007) discussed potential reasons for this difference, which is most likely due to global atmospheric circulation changes over the last several decades in spring, and cancellation of this effect in autumn.

Sierra Nevada region temperature trends

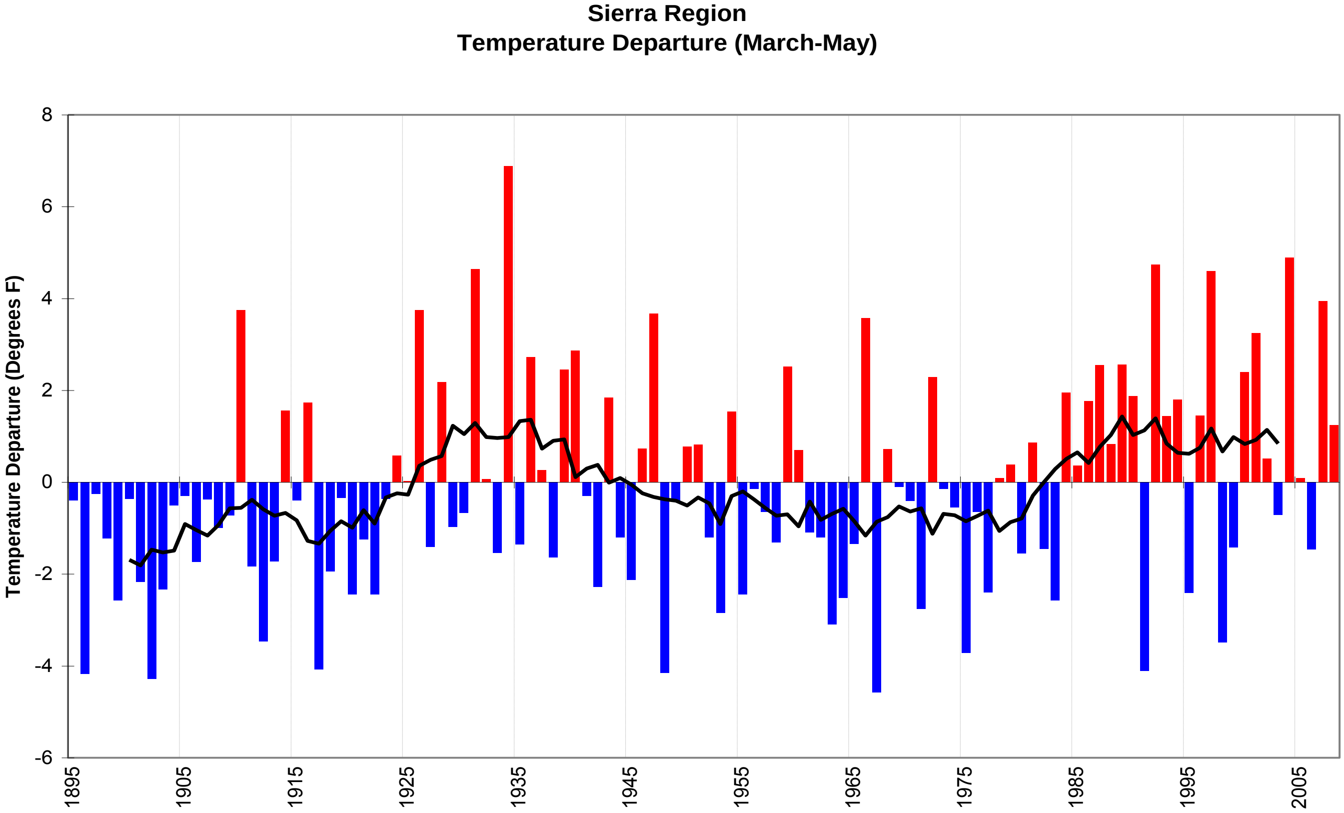
The Sierra Nevada region of California is a key geographic and climatological zone due to the natural winter snowpack storage for the state’s warm season water supply. The Sierra Nevada region used here encompasses an area approximately from the Feather River in the north to the Kern River in the south, and from about the 2000-foot elevation line on the western slope to US 395 and the west side of Lake Tahoe on the eastern slope.

Annual temperature trends in this region indicate general warming as is seen in the statewide averages, and in most climate zones in the state. The greatest warming trends in the Sierra Nevada are in late winter and spring, when there are large implications for early snowmelt and summer water supply.



Source: DRI, 2008

Sierra Nevada annual (Jan-Dec) temperature, expressed as departures from long-term average. Red is maximum temperature, blue is minimum temperature, black is mean temperature. Bold lines are the 11-year running mean.



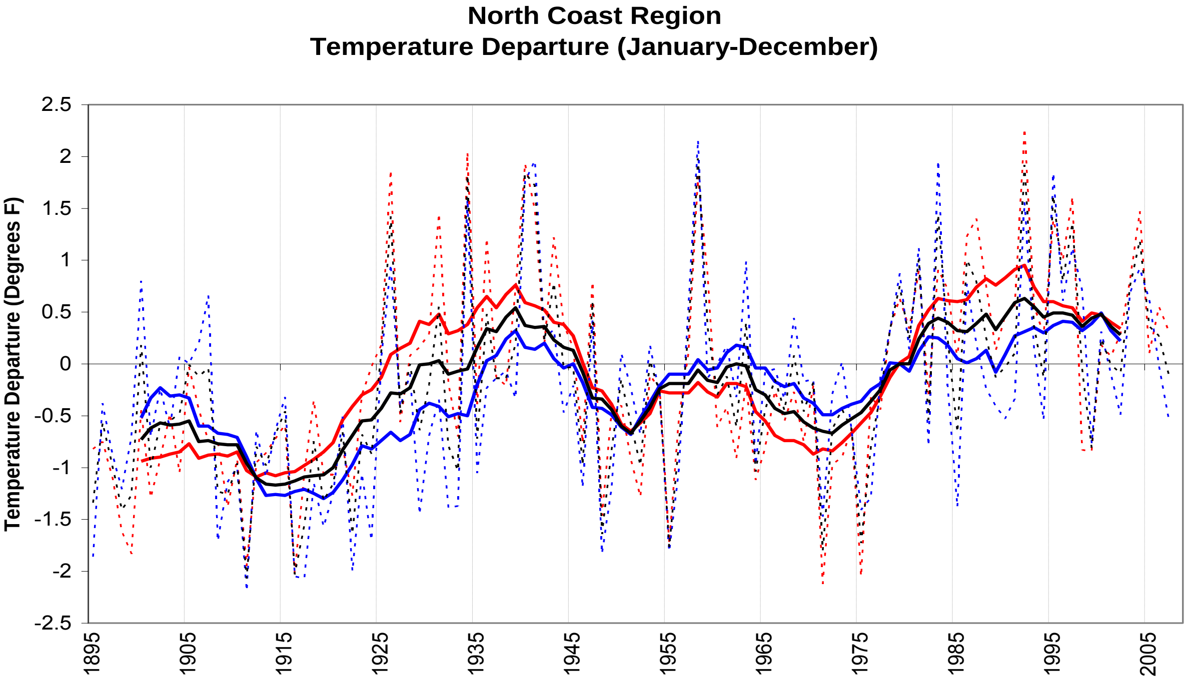
Source: DRI, 2008

Sierra Nevada region spring (March-May) minimum temperature departure from long-term average. Red indicates above average seasonal temperature, and blue indicates below average. Bold line is the 11-year running mean.

Of interest is the spring season minimum temperature departure from historical average. The increase in minimum temperatures reflects the fact there has been a decrease in the number of days where temperatures are below freezing, an important ingredient for retaining snowpack. The Sierra Nevada region used here includes a large portion of the mid-slope of the range that lies on the rain-snow line during the spring and fall seasons. Water supplies benefit from cooler conditions, when precipitation falls as snow rather than rain. Recent research has demonstrated that this mid-slope region has already experienced more rain events than the long-term average (Knowles et al., 2006).

Coastal region temperature trends

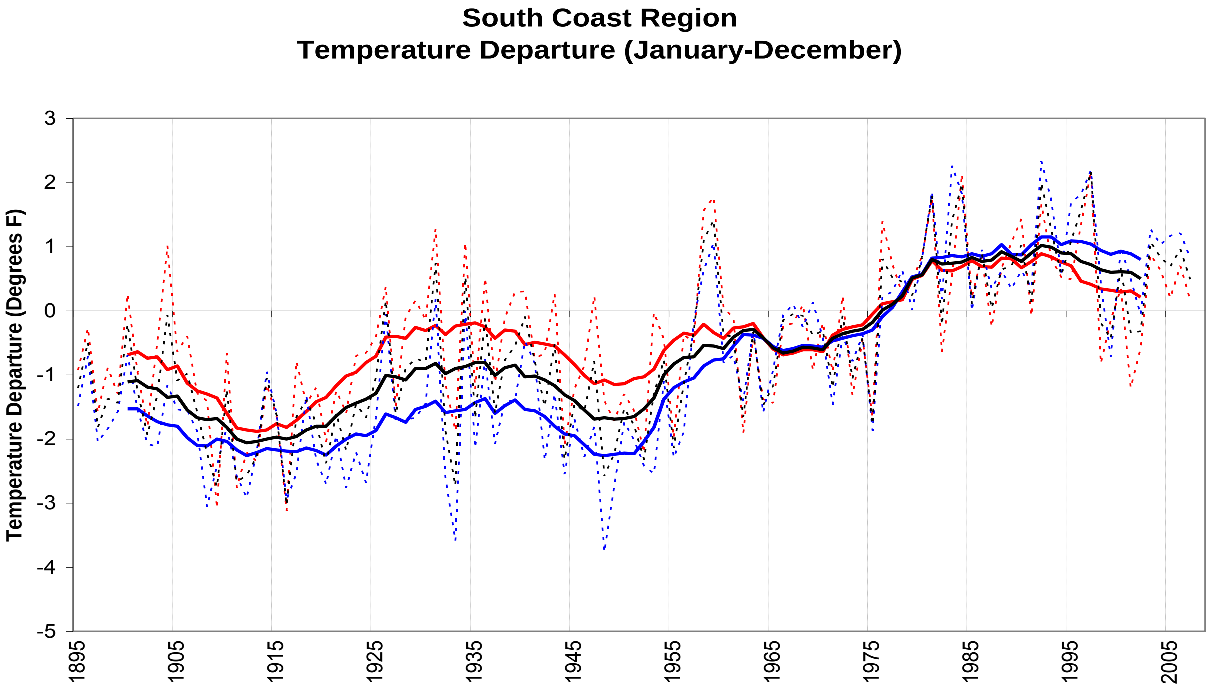
The North Coast and South Coast regions of California show smaller temperature trends than that of most of the rest of the state in the last three decades. In the North Coast region, a narrow strip from the Oregon border to just south of Point Reyes, the mean temperature departure from average is a nearly flat line. There has been some variability in the last 20 years, but the steep rate of increasing temperatures that is seen in the statewide trend is not present in the North Coast. The graph shows that the mean annual temperatures (bold black line) of the last two decades are similar to those of the 1930s.



Source: DRI, 2008

North Coast region annual (Jan-Dec) temperature, expressed as departures from long-term average. Red is maximum temperature, blue is minimum temperature, black is mean temperature. Bold lines are the 11-year running mean.

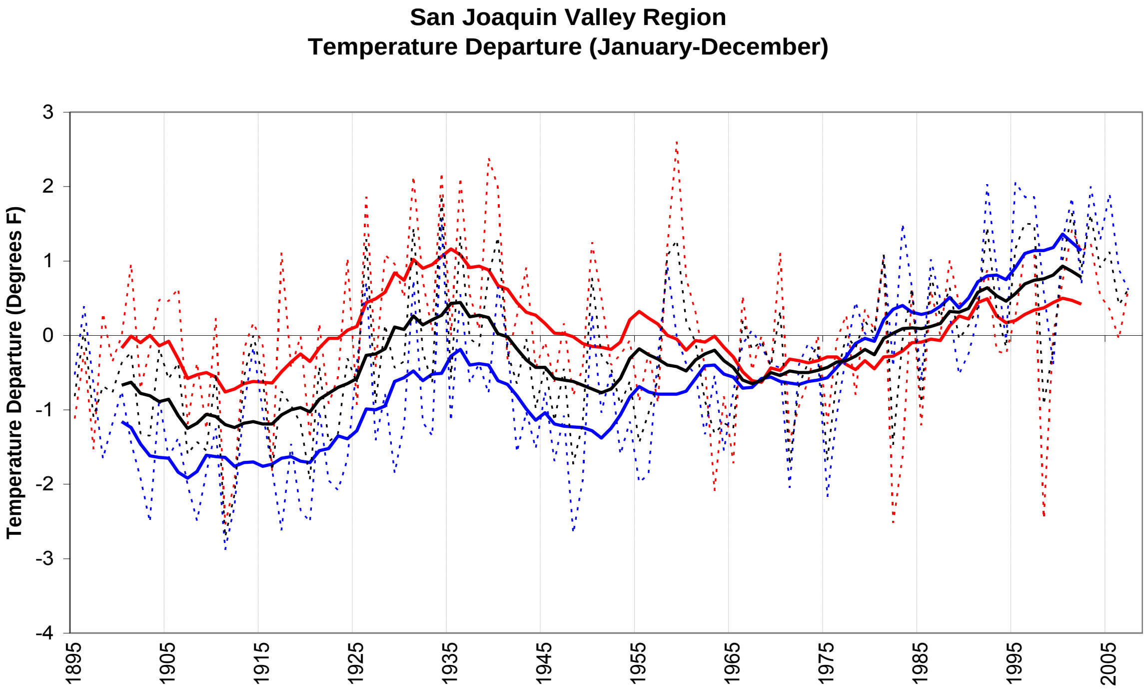
The South Coast region, in comparison to the North Coast region, has experienced an overall large warming trend over the period of record from 1895 to present. This region encompasses a narrow band from Point Conception to the Mexican border, including the Los Angeles Basin and San Diego. Despite the overall warming trends, the temperatures for the coasts have decreased. They have even leveled over the past quarter century. Attribution of the cause of this cooling or lesser warming trend is unclear at this time, but possible influences could be from increased coastal fog or marine stratus clouds, or trends in near coastal waters, although this seems less likely. Future research will delve into these possibilities more thoroughly.



Source: DRI, 2008

South Coast region annual (Jan-Dec) temperature, expressed as departures from long-term average. Red is maximum temperature, blue is minimum temperature, black is mean temperature. Bold lines are the 11-year running mean.

San Joaquin Valley temperature trends



Source: DRI, 2008

San Joaquin Valley region annual (Jan-Dec) temperature, expressed as departures from long-term average. Red is maximum temperature, blue is minimum temperature, black is mean temperature. Bold lines are the 11-year running mean.

The California Climate Tracker shows an increasing temperature trend in the San Joaquin Valley region since the mid-1970s. The figure above also indicates that minimum temperature is rising faster than maximum temperature. This region has been the focus of much research in recent years, investigating the possible role of irrigation on temperature trends (e.g., (Christy et al., 2006; Bonfils and Lobell, 2007)). Comparisons have been made between the lower elevation climate records in the valley and the higher elevation climate stations in the Sierra foothills, using other climate data sets (Christy et al. 2006). Some uncertainty remains as to the magnitude of the impact of irrigated agriculture (a change in land use in the last century) on the observed temperature trends.

Technical Considerations:

Data Characteristics

Temperature data for nearly 200 climate stations in the NOAA Cooperative Network within California were obtained from the Western Regional Climate Center database archive of quality controlled data from National Climatic Data Center. For this study, data from 1948-2007 were utilized for the long-term average. Gridded climate data from Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1997) was acquired from the PRISM group at Oregon State University for the period 1895-2007. PRISM provides complete spatial coverage of the state, where the station data serve to fill in recent data, until PRISM is processed each month. Because climate stations are not evenly spaced, the PRISM data are used to provide even and complete coverage across the state. These are combined to create a time series of annual statewide mean temperature dating back to 1895.

Over these 113 years, maximum temperatures rise at the rate of 1.07°F per 100 years, minimums rise at 2.03°F per 100 years, and mean temperatures at 1.55°F per 100 years. These rates are accurate to within about ±0.5°F. This operational product, the California Climate Tracker, is updated monthly online at the Western Regional Climate Center http://www.wrcc.dri.edu/monitor/cal-mon/index.html. Software and analyses were produced by Dr. John Abatzoglou at the Western Regional Climate Center (Abatzoglou et al., Submitted).

Strengths and Limitations of the Data

The datasets used in this work were subjected to their own separate quality control procedures, to account for potentially incorrect data reported by the observer, missing data, and to remove inconsistencies such as station relocation or instrument change. The PRISM data offers complete coverage across the state for every month of the record. Limitations include the bias of station data toward populated areas, and limited ability of quality control processes in remote or high terrain areas. The results cited here offer a hybrid using both gridded (full coverage) and station data, which is suggested to be more robust than either data set used independently (Abatzoglou et al., Submitted).

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For more information, contact:

Laura Edwards
Division of Atmospheric Science
Desert Research Institute
2215 Raggio Parkway
Reno, NV 89512
(775) 674-7163
laura.edwards@dri.edu

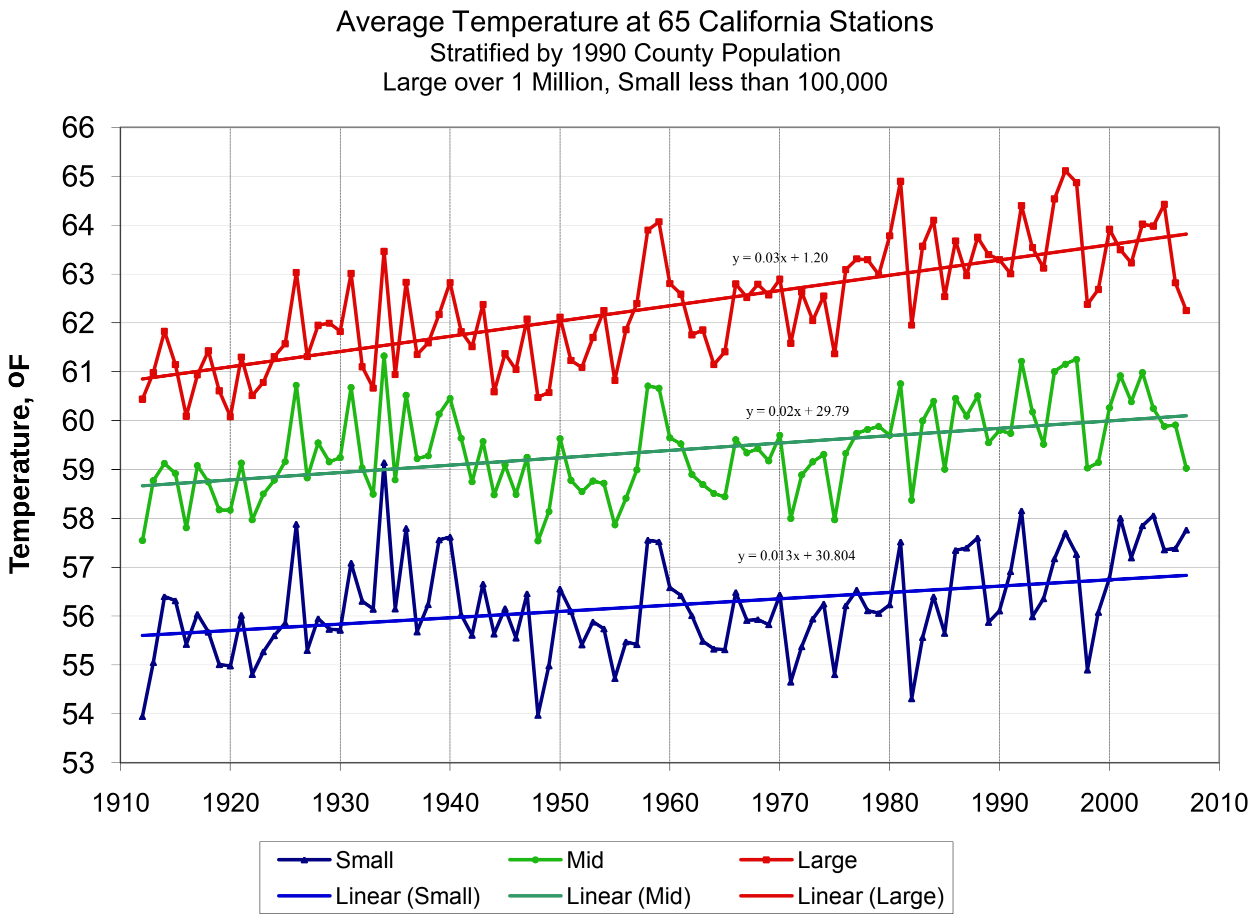
John Abatzoglou
One Washington Square, Building DH
Meteorology Department, San Jose State University
San Jose, CA 95912
(408) 924-5200
John.abatzoglou@sjsu.edu

Guido Franco
Environmental Protection Division
California Energy Commission
1516 9th Street, MS 40
Sacramento, California 95814-5504
(916) 654-3940
gfranco@energy.state.ca.gov

Changes in climate

AIR TEMPERATURE BY COUNTY POPULATION

Air temperatures have increased 0.7 to 3.0°F in the past century.



Source: DRI, 2008 (Data); DWR, 2008 (analysis)

What is the indicator showing?

Air temperature has increased over the past 90 years, more so in large cities than in rural areas. The indicator illustrates trends of average yearly temperatures for three groups of counties. Counties with the largest populations (over one million residents) had the highest temperature increase. Conversely, counties with less than 100,000 people had the lowest average rate of temperature increase. These tend to be rural areas and are more likely to be representative of global influences, natural and man-made. The rate of temperature increase -- 0.7°F (0.5°C) per century -- from the rural group agrees with a global estimated mean surface temperature increase of 0.5 to 1.0°F (0.3 to 0.6°C) since the 19th century.

Why is the indicator important?

Temperature provides a direct indication of climate change, and is an important factor affecting natural systems and human activities. The indicator allows for a comparison of long-term (almost a century-long) temperature changes in California among counties with small, average and large populations.

What factors influence this indicator?

Most of the observed increases in global average temperatures since the mid-twentieth century is very likely due to the observed increase in greenhouse gas concentrations as a result of human activities (IPCC, 2007). Atmospheric concentrations of the greenhouse gases carbon dioxide, methane, nitrous oxide and halocarbons have all increased since pre-industrial times. Carbon dioxide, the most important of the greenhouse gases, primarily originates from fossil fuel use, with changes in land use providing another significant but smaller contribution.

As shown in the graph, counties with large populations -- which tend to be those with large urban areas -- are generally warmer than those with small populations which are generally in rural areas. Urban areas can have temperatures up to 5°F higher than rural areas, creating their own weather belt. This can be due to the removal of vegetation and trees, the presence of buildings and streets (which reflect heat stored in pavement), and the production of heat by human activities.

In addition to degree of urbanization – for which total county population is used as a surrogate -- local geographical features also affect temperatures in the many diverse areas that make up California. With the wide range of geographic differences in the state, on any given summer day, California may experience both the hottest and the coldest air temperatures in the continental United States. Ocean currents upwelling and sea surface temperatures along the coast of California influence air temperatures; seasonal variations also occur (The Union of Concerned Scientists and The Ecological Society of America, 1999). Changes in temperature and flow patterns in the Northern Pacific (Hare, 2000) and in the Eastern tropical Pacific (El Nino Southern Oscillation) cause variations in storm tracks affecting California. The mountains are also a strong influence and sometimes create their own weather. It is possible that changing vegetation cover and the evaporative cooling effects of irrigated crops in the Central Valley may influence summer temperatures to a slight degree.

Technical Considerations:

Data Characteristics

California temperature data from the Western Regional Climate Center (WRCC, 2008) located in Reno, Nevada were collated and studied by James Goodridge (Goodridge, 2001). Average yearly temperature data from recording stations located throughout California were stratified by county population size into three groups: sites in counties with a population of over one million persons; sites in counties with a population of less than 100,000; and sites in counties with populations that fall in between.

Strengths and Limitations of the Data

The location of the temperature recording stations may not have remained consistent over the years. The rural stations tend to be biased toward interior (eastern) counties of California, while most of the other sites are found along the coastal zone, so some of the contrast seen in temperature trends may be from geographic differences, rather than urban effects. In addition, the landscape surrounding the station may have changed with urbanization, and heated buildings or devices may have impacted the thermometer readings. Temperatures at airport weather stations may be influenced by radiant heat from the runways. Future data sets for this indicator may be refined to reflect a subset of select temperature monitoring sites that have been screened to have few confounding factors. Although new instruments have been developed, they were not calibrated with the equipment they have replaced. Fortunately, thermometers that have been used over the decades are deemed to be as reliable as current instruments. Historically, volunteers staff weather stations throughout the state. The volunteers select the time of day they wish to consistently record the maximum and minimum temperatures.

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For more information, contact:

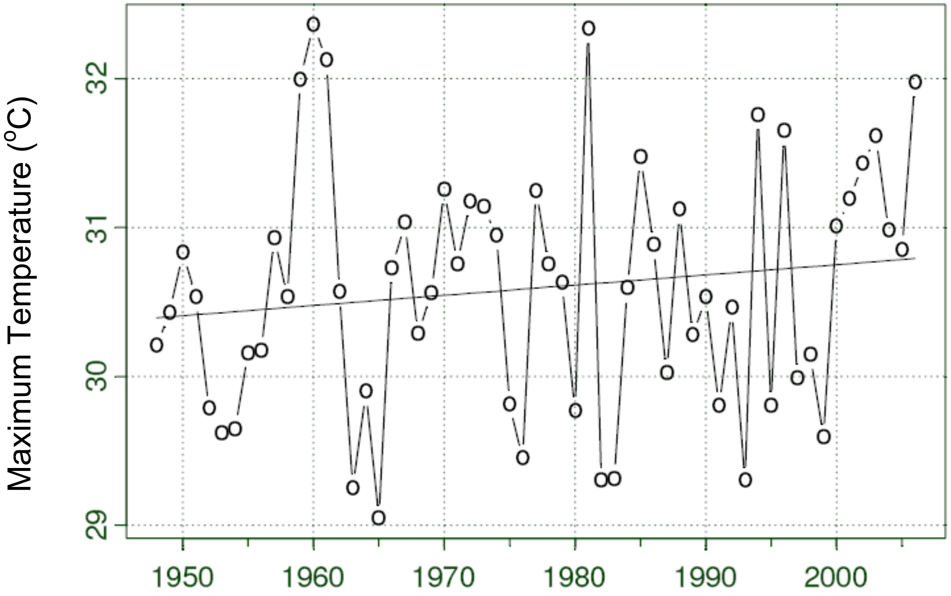
Michael Anderson
State Climatologist
California Department of Water Resources
3310 El Camino Ave., 200
Sacramento, CA 95821
(916) 574-2830
manderso@water.ca.gov

Changes in climate

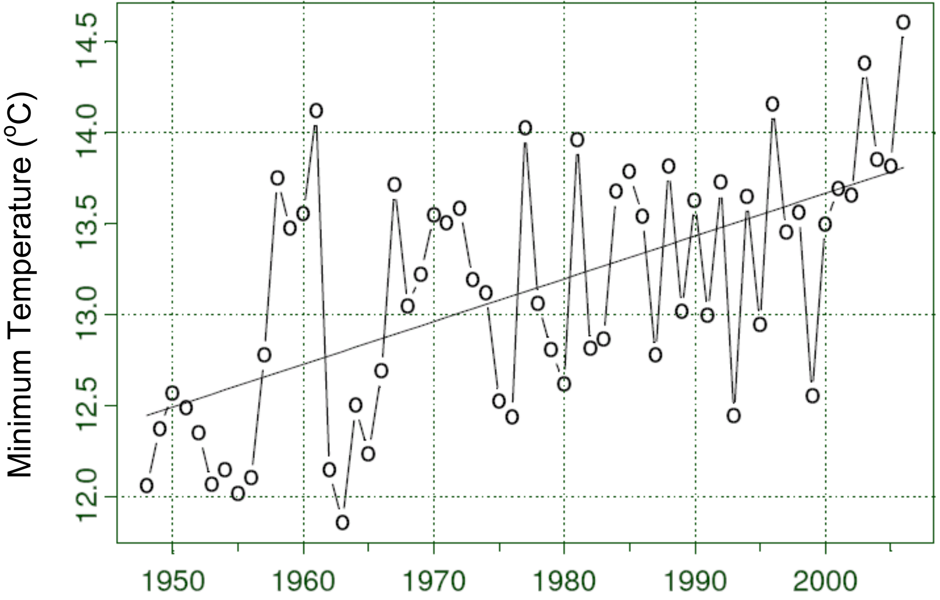
EXTREME HEAT EVENTS

Summertime temperature extremes are on the rise especially at night; the nighttime heat wave activity in 2006 was unprecedented in the six-decade record.

SUMMERTIME* MAXIMUM TEMPERATURE (averaged over 95 stations)



SUMMERTIME* MINIMUM TEMPERATURE (averaged over 95 stations)



Source: NCDC, 2007 (data); Gershunov, 2008 (analysis)

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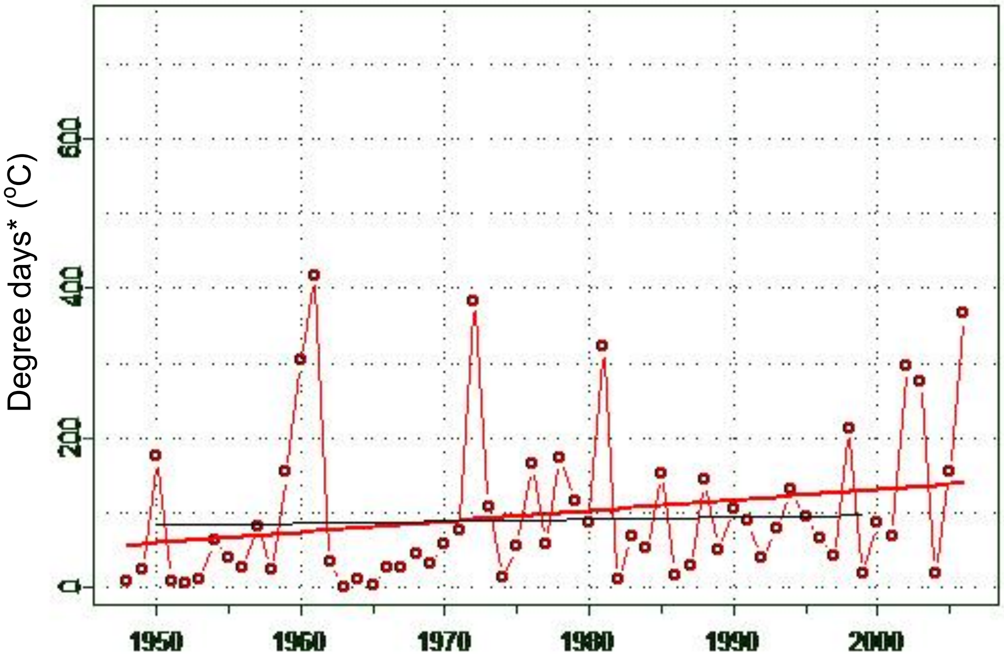
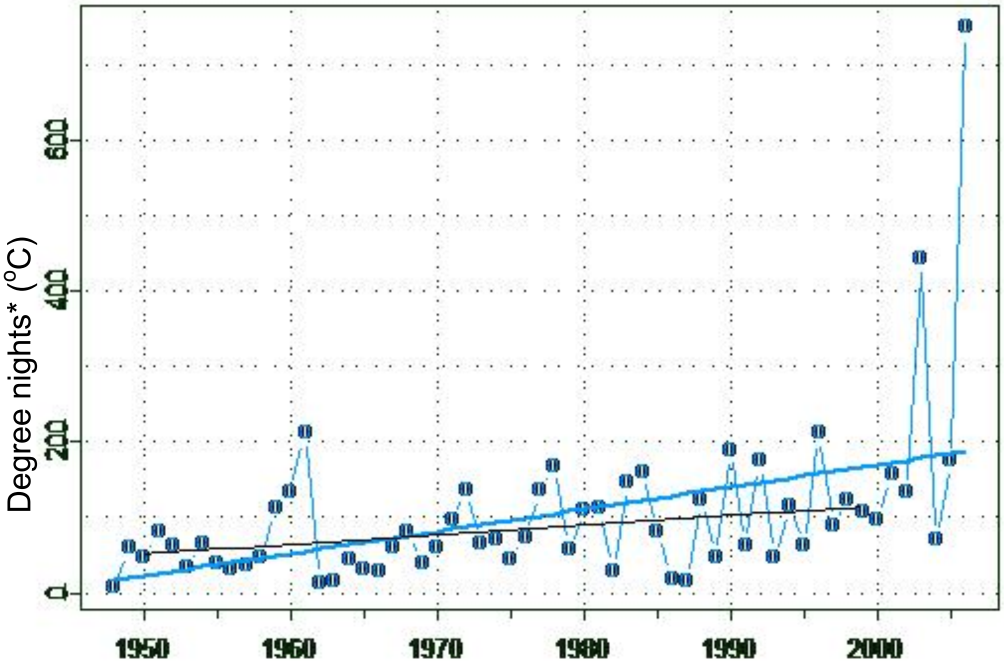
* Summertime includes June, July and August.

REGIONAL HEAT WAVE INDICATORS*

Daytime heat wave indicator



Nighttime heat wave indicator



Source: NCDC, 2007 (data); Gershunov, 2008 (analysis)

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* Values – expressed as "degree days" or "degree nights" -- are summations of daily threshold exceedances (i.e., temperatures above the 99th percentile for each station) for each summer (June 1 through August 31) of each year over all stations, and reflect intensity, frequency, duration and regional extent of the heat wave. Linear regression lines are shown for the entire record (1948-2006, colors) and over the base period (1950-1999, black).

What is this indicator showing?

Summertime (June to August) maximum (Tmax) and minimum (Tmin) temperatures have increased between 1948 and 2006. The first set of graphs show summertime maximum and minimum temperatures for each year, averaged over 95 climate stations in California and Nevada. Tmax reflects the hottest daytime temperatures, while Tmin reflects the coolest nighttime temperatures.

The Tmax, averaged over the California and Nevada region, increased by 0.07°C per decade, or 0.4°C over the 59-year record. The region-averaged Tmin increased at a greater rate of 0.24°C per decade, or 1.4°C over the same time period. Global average temperatures increased by 0.13°C per decade, or 0.76°C over the same six-decade period (Hansen et al., 2001). The average summertime regional warming observed over California and Nevada is fully consistent with the annual average global warming observed over land areas in worldwide station records.

The second set of graphs, the regional heat wave indicators, reflects summertime heat wave activity across the 95 climate stations. By definition, daytime or nighttime heat waves occur when the Tmin or Tmax for that day exceeds a station-specific high temperature threshold. This temperature threshold for a given station is the value corresponding to the 99th percentile of the daily maximum (for the daytime heat wave indicator) or daily minimum (for the nighttime heat wave indicator) temperatures recorded over the period from 1950 to 1999. For each station, the heat wave indicator is derived as the sum of exceedances over the 99th percentile from June 1 through August 31 of each year. The summation of these total exceedances for all of the stations over the entire region is plotted as the value — either as degree days or degree nights — for that year. Hence, the magnitude of the heat wave indicator is a function of the intensity, frequency, duration and regional extent of the daytime and nighttime heat patterns.

Although there were intermittent years with intense daytime heat activity (1960, 1961 and 1972) in earlier years, a shift to generally higher activity occurred in the mid-1970s; this is consistent with the increasing average annual temperatures for the same time period. The slight upward trend in daytime heat wave activity is mostly due to the increases seen in more recent years. In contrast, the increasing trend in nighttime heat wave activity has been occurring over the entire period shown, with sharp, unprecedented increases first in 2003, then in 2006.

Why is this indicator important?

Increases in both minimum and maximum temperatures, particularly during the summer, are projected to have public health, ecological, and economic impacts, such as heat-related deaths and illnesses, decreased agricultural production, and greater demands on California's electricity supply. Excess deaths occur during heat waves and on days with higher than average temperatures; less information exists on temperature-related illnesses (CCSP, 2008). The impacts of extreme heat events are mediated by factors affecting the vulnerability, resiliency and capacity of a system for adaptation. Hence,

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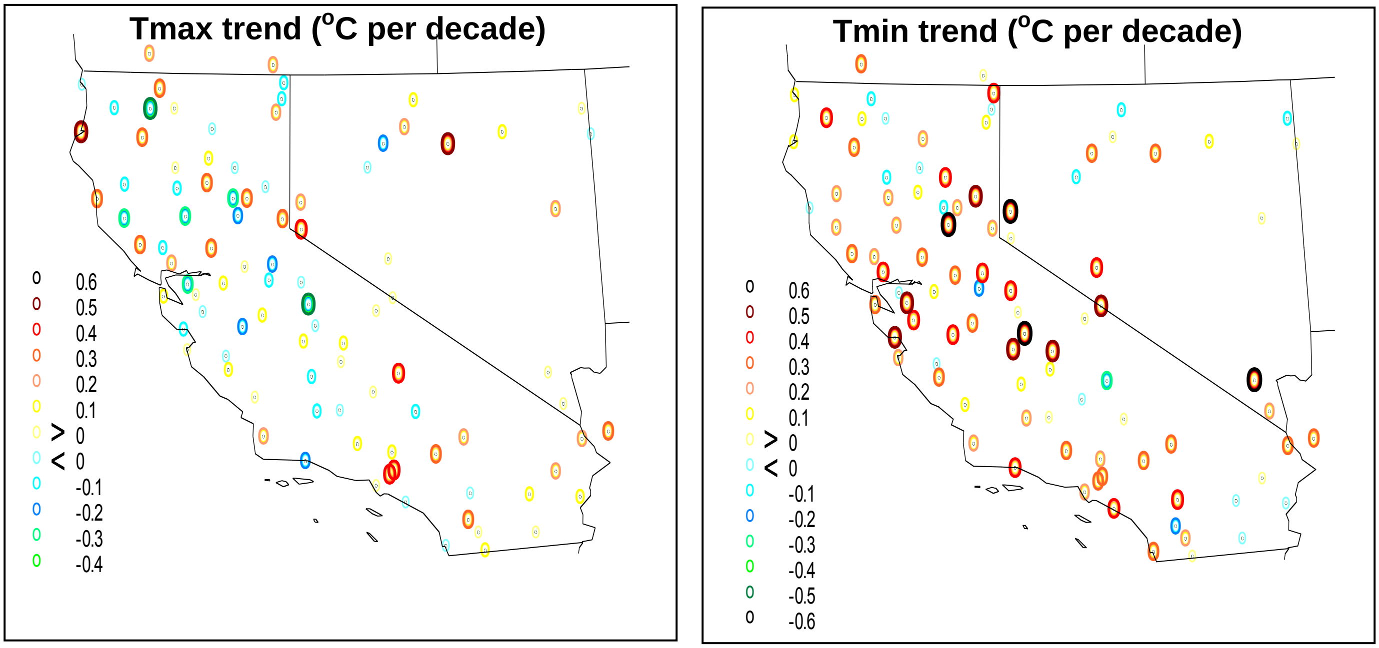
It is important to evaluate daytime and nighttime temperatures separately. Such analyses will help explain some of the processes and potential effects of climate change. It is worth noting that a major cause of heat-related deaths is the lack of night cooling that would normally allow a stressed body to recover. The increase in summertime *minimum* temperatures therefore presents an additional risk factor for already vulnerable populations.

What factors influence the indicators?

Air temperature varies according to the time of day, the season of the year, and geographic location. Some of the stations that showed the greatest increases in minimum temperature are in urban areas, as would be expected due to the "urban heat island effect" (see maps below). Urbanization, however, does not explain the bulk of the nighttime warming observed. Rural stations are warming considerably at night. Nevada City, a gold rush town in the low Sierra Nevada, records the largest Tmin trend (1.3°C per decade). Auberry, in the Sierra Nevada foothills between Fresno and South Yosemite entrance comes in third with 0.99°C per decade. Many other rural stations are warming at about 0.4°C per decade at night.

Summertime daytime (Tmax) and nighttime (Tmin) temperature trends*
1948-2006



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* Colored circles around the stations represent the sign and magnitude of the trend (according to the values on the legend); larger circles depict greater trends.

According to the data, the highest temperature extremes during both day and night typically occur in the southeastern low deserts and interior valley regions, while the high Sierra Nevada and along the coastal ranges experience the lowest temperatures.

The recent intensification in nighttime heat wave activity is mainly due to the increased humidity of the heat waves over the region. High nighttime temperatures accompanied by high humidity during the day and night have made the recent heat waves, especially the event of 2006, more taxing on energy resources as well as more dangerous for human and animal health.

Technical Considerations:

Data Characteristics

Temperature data are from the National Climatic Data Center, DSI-3200 database (NCDC, 2003). This database is comprised primarily of stations in the National Weather Service (NWS) cooperative station network. While the vast majority of the observers are volunteers, the network also includes the NWS principal climatological stations, which are operated by highly trained observers. The period of record and number of stations varies among the states. Most states began collecting data during 1948, although some began in 1946.

The observing equipment used at all of the stations, whether at volunteer sites or federal installations, are calibrated and maintained by NWS field representatives, Cooperative Program Managers, and Hydro-Meteorological Technicians.

Strengths and Limitations of the Data

The data have received a high measure of quality control through computer and manual edits, and are subjected to internal consistency checks, compared against climatological limits, checked serially, and evaluated against surrounding stations.

The data presented include stations in Nevada. California stations, however, make up the majority of the stations; hence the information is mainly representative of the State.

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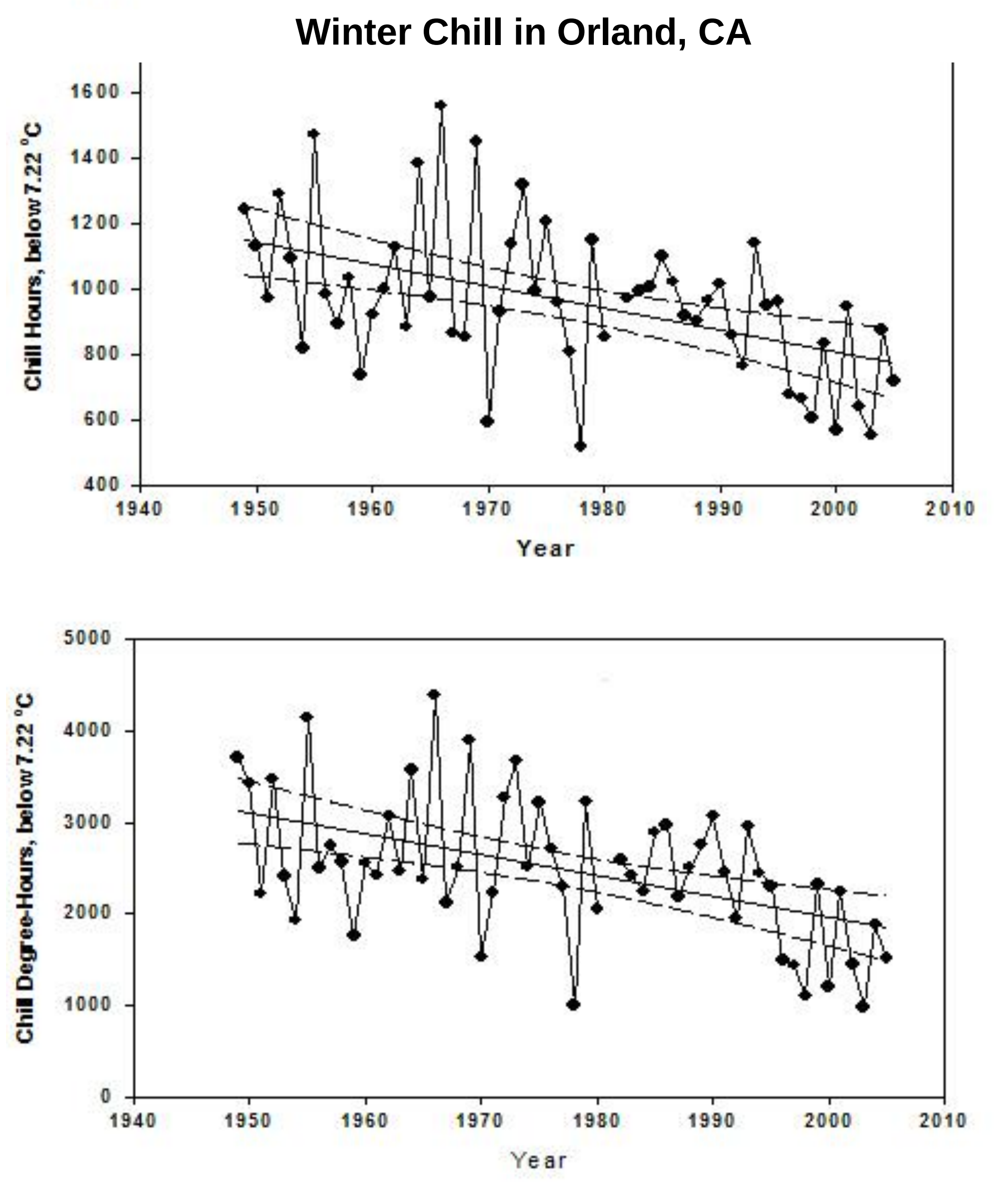
For more information, contact:

Alexander Gershunov
Scripps Institution of Oceanography
9500 Gilman Drive
La Jolla, CA 92093-0224
(858) 534-8418
sasha@ucsd.edu

Changes in climate

WINTER CHILL

Chill hours have been decreasing over the past half century.



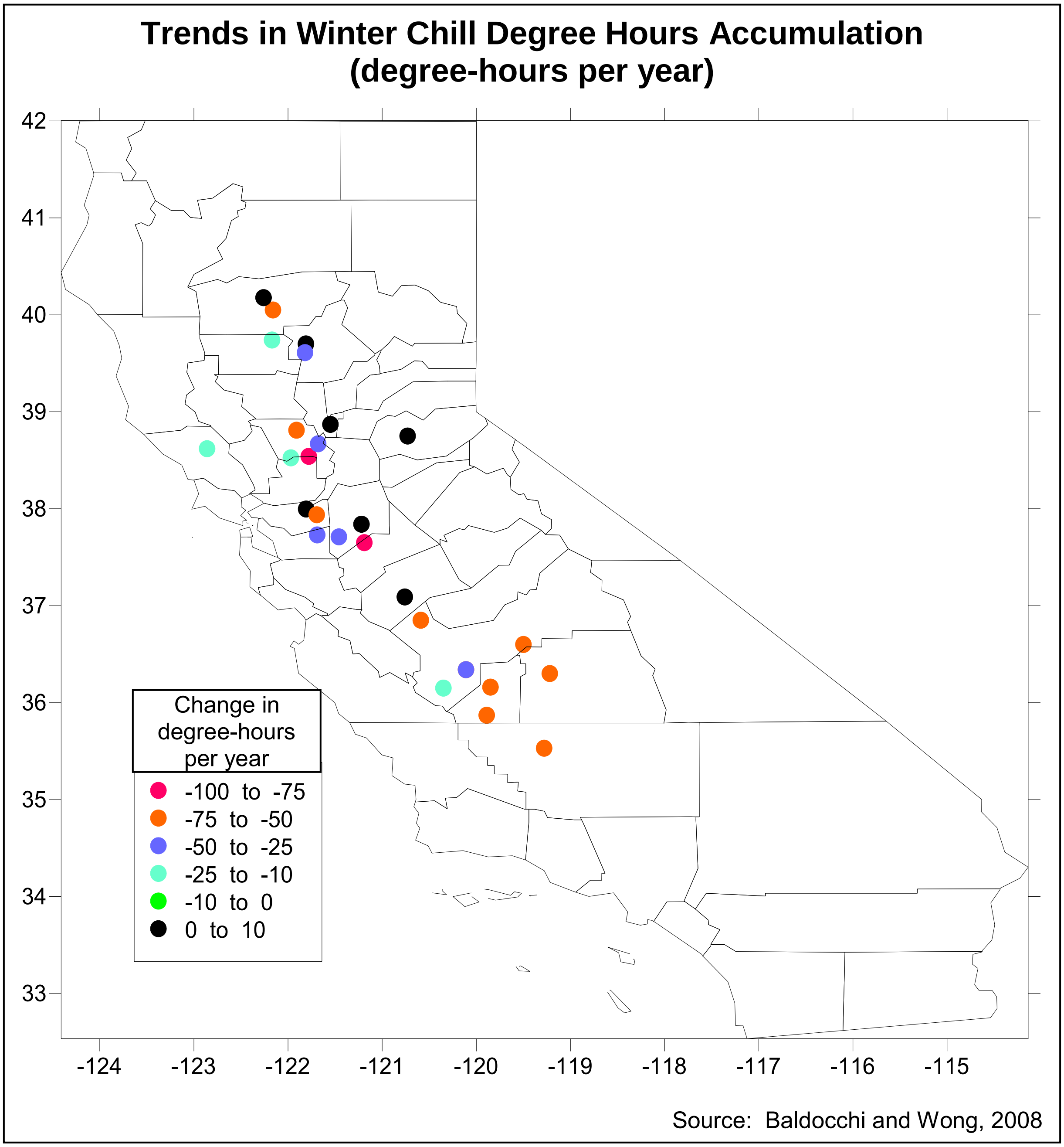
Source: Baldocchi and Wong, 2008

Regression lines (solid) with confidence intervals (dashed lines) are shown.

What is the indicator showing?

Winter chill in Orland, an agricultural town in Northern California located about 100 miles north of Sacramento, has been decreasing over the past fifty years. Many fruit trees need a critical amount of winter chill to produce flowers and fruit. In the graphs above, winter chill is expressed as (1) the number of winter hours below 7.22^{o}C (45^{o}F), a threshold temperature for dormancy; and, (2) the summation of this number of hours multiplied by the number of degrees that temperature is below 7.22^{o}C.

The same analysis was repeated on data for other climate stations across the fruit growing valleys of California (see map below). Most sites are experiencing a significant and negative trend in winter chill hours, generally ranging between 100 and 1,000 degree-hours per decade. Eight sites did not show a negative trend. No specific geographic pattern was detected.



Trends in Winter Chill Degree Hours Accumulation (degree-hours per year)

Source: Baldocchi and Wong, 2008

Why is this indicator important?

An extended period of cold temperatures below a threshold temperature is required for fruit trees to become and remain dormant, and subsequently bear fruit. In general, fruit trees need between 200 and 1,500 hours below 7.22°C during the winter to produce flowers and fruit (Baldocchi and Wong, 2006). This indicator tracks the number of hours during the winter months when the temperature is below this critical number. The companion graph further characterizes the trend in winter chill by incorporating the magnitude of the difference between observed temperatures and the critical temperature.

Temperature is a significant factor affecting the vegetation behavior. The length of the period between the last springtime frost and its first occurrence in the autumn determines the length of the growing season. Regional analyses of climate trends over agricultural regions of California, as well as the western United States, suggest that climate warming is occurring. A warming climate extends the length of the growing season, a consequence which can, in turn, lead to both positive and negative results. For example, a longer and warmer growing season can increase the yield of perennial vegetation. On the other hand, a longer growing season can reduce the length of the dormant period necessary for fruit production.

Summary statistics that are commonly used to track temperature (such as average, minimum and maximum) generally do not provide the resolution necessary to examine temperature trends relevant to agriculture. Deriving winter chill degree hours from temperature data for the winter months yields a more meaningful measure for tracking a change in climate that would be more predictive of fruit production. Winter chill degree hours provides an indication of whether specific fruit and nut trees are experiencing sufficient periods of dormancy.

Several studies conclude that current climate conditions provide the needed dormancy requirements partly as a result of prolonged periods of fog during the winter in the California Central Valley. If prolonged periods of winter fog disappear in the future, however, the Central Valley may experience larger diurnal swings in winter temperature and reduced hours below the critical temperature. Future trend projections show that continued warming will reduce the accumulated number of chill degree hours for the Central Valley. This would jeopardize the region's ability to sustain its production of high value nuts and fruits like almonds, cherries and apricots, resulting in serious economic, culinary and social consequences. Substituting other fruit species, or newly developed varieties, that need less chill hours may become necessary in the future.

What factors influence this indicator?

The indicator is derived from temperature data, and as such, is influenced by the same factors that influence temperature. An additional consideration relates to the location where temperature measurements are taken, and whether they are close enough to the areas where fruits and nuts are grown to be representative of those air temperatures.

Technical Considerations:

Data Characteristics

Winter chill degree hours were derived using a combination of hourly and daily climate data. Hourly climate data are from the California Irrigation Management Information System (CIMIS); daily data are from the National Weather Service Cooperative Network (NEW coop). While CIMIS provides ideal data for computing accumulated winter chill hours, its time series is relatively short for climate analysis, having started in the 1980s. NWS coop, on the other hand, provides data for as far back as the 1930s, but only for daily maximum and minimum temperature. The study investigators developed an algorithm based on reported maximum and minimum temperature data; the algorithm was tested and validated using the hourly climate data.

Daily chill hours are computed relative to 7.22^{o}C as the reference temperature, and summed for the period between November 1 and February 28. Temperature differences were not summed if air temperature was below freezing or above the reference level. The data for Orland are for the station that started in 1948.

Strengths and Limitations of the Data

The hourly data from CIMIS provide direct inputs into the calculation of winter chill degree hours, unlike daily minimum and maximum temperature data from NWS, which require the use of an algorithm.

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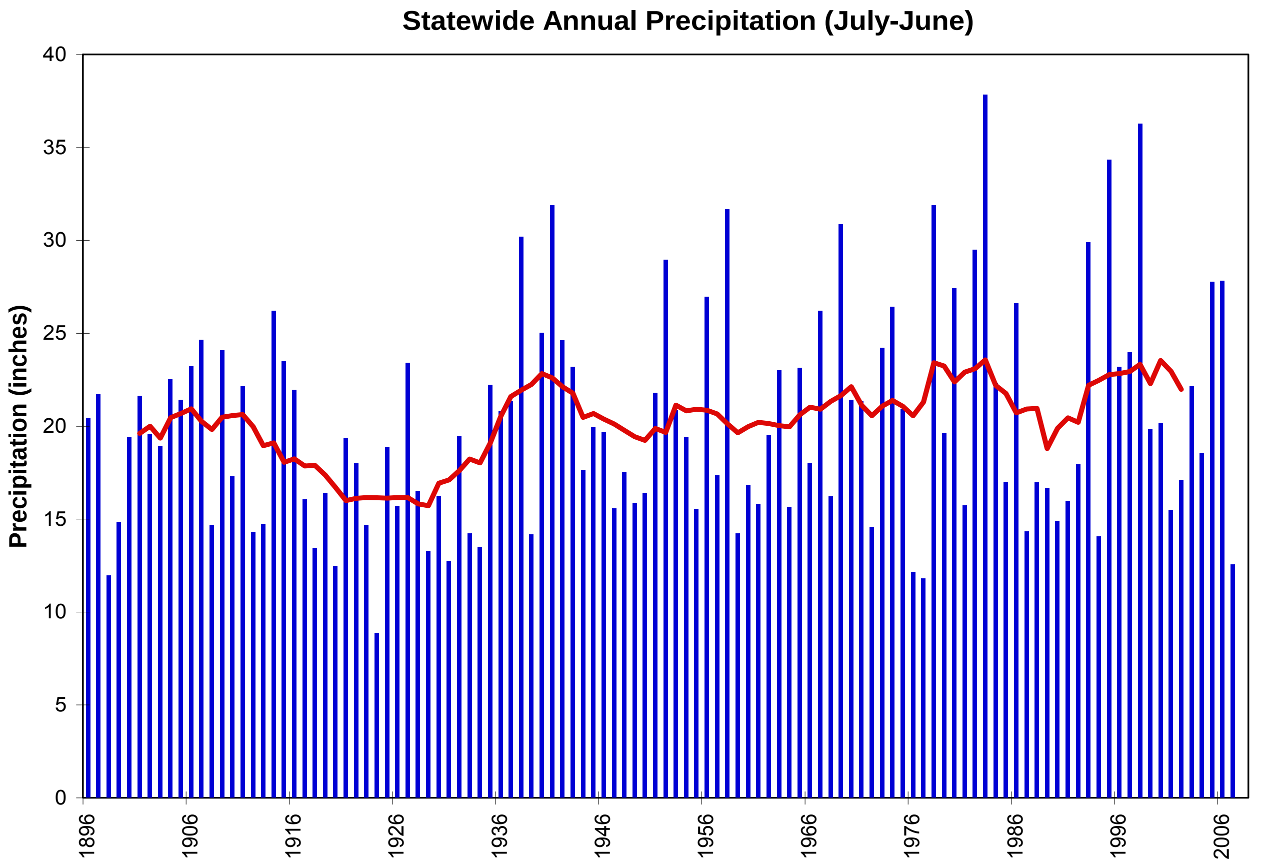
For more information, contact:

Dennis Baldocchi
345 Hilgard Hall
137 Mulford Hall
Berkeley, CA 94720-3110
(510) 642-2874
biomet@nature.berkeley.edu
baldocchi@nature.berkeley.edu

Changes in climate

ANNUAL PRECIPITATION: STATEWIDE AND REGIONAL

Little change is evident in precipitation trends.



Source: WRCC, 2008

California statewide average winter-centered (July-June) annual precipitation for 1895-2007. Bars indicate annual total precipitation. The red line is the 11-year running average.

What is this indicator showing?

California Climate Tracker provides regional and statewide temperature trends. This operational database tracker for weather and climate monitoring information is updated with recent data monthly online at the Western Regional Climate Center at www.wrcc.dri.edu/monitor/cal-mon/index.html. Over the entire 112-year period of record, the linear trend of annual precipitation is an increase of about 17 percent per century. Of note are the large year-to-year variations in precipitation, particularly since the 1930s, and long episodes of consecutive dry or wet years at many times during the observational record.

Why is this indicator important?

Precipitation in the form of rain and snow is a major component of the biological and economic lifeblood of California. The historical likelihood of wet and dry episodes of various durations must be factored into planning for management of water resources (municipal and industrial water supplies, agriculture, hydropower, recreation, fish habitat, and others) and in planning for both floods and droughts. Perspectives should reflect most likely future conditions, and be informed by the distant past and the projected future.

In light of expected warmer temperatures statewide, demand for hydropower electricity generation and water for agriculture will increase. Long-term climate projections generally call for greater concentration of precipitation in mid-winter months. Overall, relatively little change in net annual precipitation is projected for the northern tier of the state, with moderate decreases in southern California; however, overall the projection of increased rain at the expense of snowfall appears robust over all models considered. Previous research has demonstrated the concern of future limited water resources (California Climate Change Center, 2006).

An annual precipitation indicator will serve to monitor precipitation in California and 11 climate regions within the state, and may assist in planning of water resource allocation and drought monitoring activities.

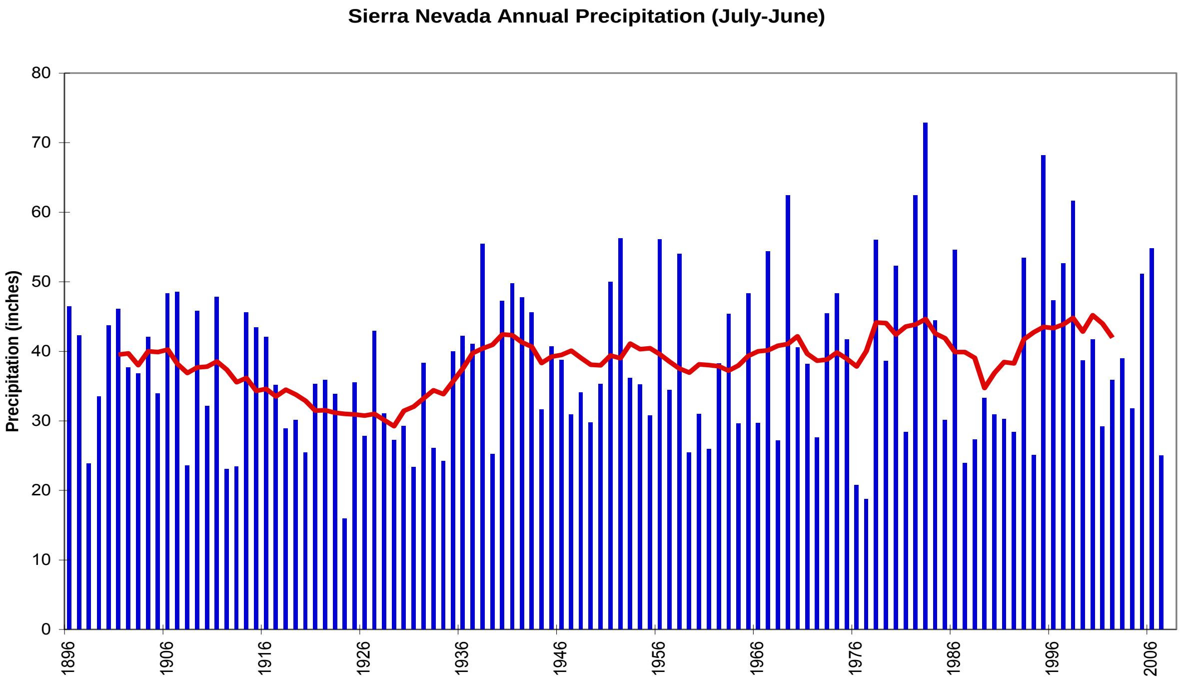
What factors influence this indicator?

Global scale weather patterns bring moisture to California, primarily from the Pacific Ocean. In California's Mediterranean climate, summers are typically dry and the wet season occurs in the winter (October-March). In the southeastern desert regions, including the Sonora and Mojave deserts, some monsoonal activity in the summertime may bring thunderstorm precipitation.

California experiences significant variation in precipitation, particularly in the south, which has the highest relative variability in the United States. These variations are related to El Niño and La Niña in the tropical Pacific, and to conditions in the northern Pacific and near Indonesia. Ocean conditions change slowly, over periods of months to years to decades, with similarly prolonged effects on adjacent land.

Local terrain can also influence precipitation. For example, elevated terrain (such as a mountain range) often causes precipitation where none would have occurred otherwise, and almost always enhances the amount from existing storm systems. As the atmosphere is pushed up the slope of the range, the water vapor cools and condenses if the air is moist enough. This often forms clouds on the upslope and over the mountain crest, and can cause precipitation to fall. This phenomenon is called orographic forcing.

Sierra Nevada region precipitation trends



Source: WRCC, 2008

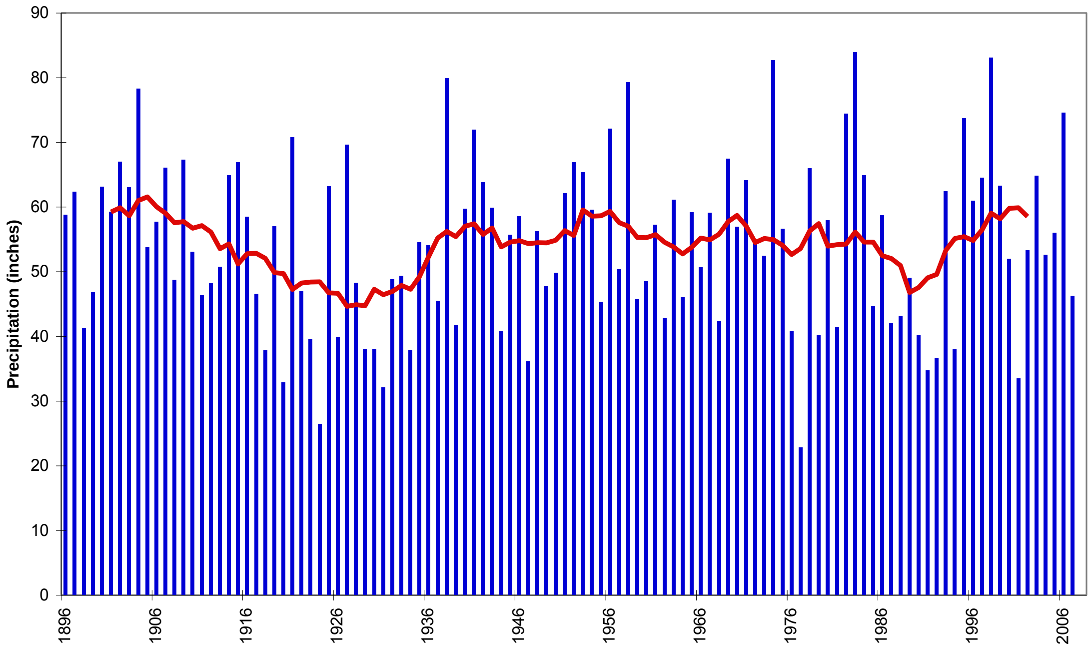
Sierra Nevada region winter-centered (Jul-Jun) precipitation. Bars indicate annual totals. The red line is the 11-year running average.

The Sierra Nevada region of California is a key geographic and climatological zone where natural winter snowpack storage provides the warm season water supply. The Sierra Nevada region used here encompasses an area approximately from the Feather River in the north to the Kern River in the south, and from Highway 99 on the western slope to US 395 and the west side of Lake Tahoe on the eastern slope.

Precipitation in the Sierra Nevada has major statewide impact and thus draws intense interest. The last 35 years have brought the wettest and driest winters in this 112-year record, and several multi-year wet and dry periods. Dry years since and including 1976-77 have approached the driest single year ever in 1924. Since 1940, however, the 11-year running mean gives little indication of either an increasing or decreasing trend in Sierra precipitation. This indicator, in combination with other snowfall and runoff measurements, can provide timely information during the winter snowpack season.

Coastal region precipitation trends

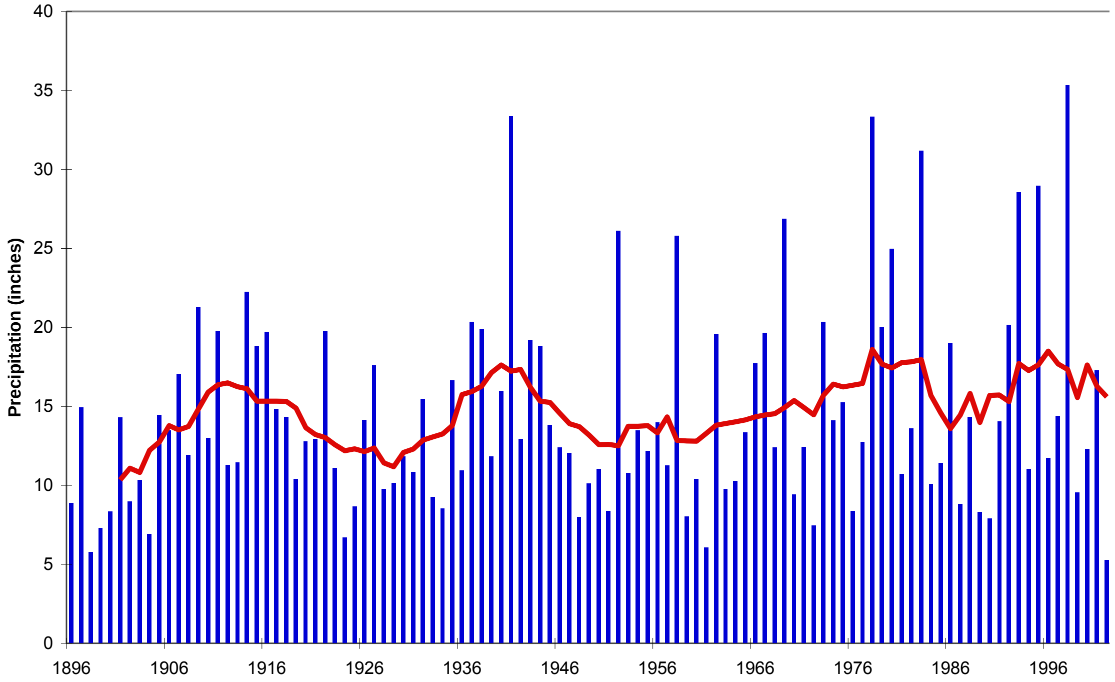
North Coast Annual Precipitation (July-June)



Source: WRCC, 2008

Annual (Jul-Jun) precipitation for the North Coast climate region. Bars indicate annual totals. The red line is the 11-year running average.

South Coast Annual Precipitation (July-June)



Source: WRCC, 2008

Annual (Jul-Jun) precipitation for the South Coast climate region. Bars indicate annual totals. The red line is the 11-year running average.

The large difference in average annual precipitation between the northern and southern California coasts is evident, with the North Coast averaging 55.32” per year, and the South Coast averaging 15.51” per year. In both cases, however, running means do not indicate much trend, neither increasing nor decreasing. For the North Coast, the linear trend for 1895-2007 is +1 percent per century with uncertainty of 13 percent. The North Coast has half as much relative variability (24 percent of the annual mean) as does the South Coast (49 percent). Along the North Coast, 1967-1977 was the driest winter, in contrast to 1923-1924 for the state. Starting in 1940 there is evidence of a modest increase in extreme wet years along the North Coast.

The South Coast has an upward trend in precipitation of +23 percent per century with uncertainty of 24 percent, and little evidence of a projected decrease from climate change. For the South Coast, 2006-2007 was the driest winter, just after its two wettest winters. A dramatic increase along the South Coast started around 1940, similar to the North Coast, with an even further increase there starting about the middle 1970s.

Technical Considerations:

Data Characteristics

Precipitation data for nearly 200 climate stations in the NOAA Cooperative Network (COOP) within California were obtained from the Western Regional Climate Center database archive of quality controlled data from National Climatic Data Center. For this study, COOP data from 1948-2007 were utilized. Gridded climate data from Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly, 1997) was acquired from the PRISM group at Oregon State University for the period 1895-2007. PRISM provides complete spatial coverage of the state, where the station data serve to fill in recent data, until PRISM is processed each month. Because climate stations are not evenly spaced, the PRISM data are used to provide even and complete coverage across the state. These are combined to create a time series of annual statewide precipitation dating back to 1895.

This indicator uses a “precipitation-year” defined as July 1 to June 30. This is more useful than a calendar year in California due to the typically dry summer and wet winter (“Mediterranean”) climate. This operational product, the California Climate Tracker, is updated monthly online at the Western Regional Climate Center http://www.wrcc.dri.edu/monitor/cal-mon/index.html. Software and analyses were produced by Dr. John Abatzoglou at the Western Regional Climate Center (Abatzoglou, Submitted).

Strengths and Limitations of the Data

The datasets used in this work were subjected to their own separate quality control procedures, to account for potentially incorrect data reported by the observer, missing data, and to remove inconsistencies such as station relocation or instrument change. The PRISM data offers complete coverage across the state for every month of the record. Limitations include the bias of station data toward populated areas, and limited ability of quality control processes in remote or high terrain areas. The results cited here offer a hybrid using both gridded and station data, which is suggested to be more robust than either data set used independently (Abatzoglou et al. 2008).

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For more information, contact:

Laura Edwards
Division of Atmospheric Sciences
Desert Research Institute
2215 Raggio Parkway
Reno, NV 89512
(775) 674-7163
laura.edwards@dri.edu

John Abatzoglou
One Washington Square, Building DH
Meteorology Department, San Jose State University
San Jose, CA 95912
(408) 924-5200
John.abatzoglou@sjsu.edu

Guido Franco
Environmental Protection Division
California Energy Commission
1516 9th Street, MS 40
Sacramento, California 95814-5504
(916) 654-3940
gfranco@energy.state.ca.gov

IMPACTS OF CLIMATE CHANGE ON PHYSICAL SYSTEMS

Climate is a key factor affecting the characteristics of natural systems. Assessment of global data since 1970 by the IPCC (2007) has shown that natural systems in all continents and most oceans are being affected by regional climate change, particularly temperature increases. The assessment further concludes that it is likely that human-induced warming has had a discernible influence on physical and biological systems.

INDICATORS: IMPACTS OF CLIMATE CHANGE ON PHYSICAL SYSTEMS[*]

- Annual Sierra Nevada snowmelt runoff
- Snow-water content
- Glacier change
- Sea level rise
- Lake Tahoe water temperature
- Delta water temperature
- Coastal ocean temperature
- Oxygen concentrations in the California Current

Reference:

IPCC. (2007). *Technical Summary. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Reprot of the Intergovernmental Panel on Climate Change*. Cambridge University Press. http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

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[*] Unless otherwise noted, environmental indicators listed are classified as "Type I" (see page 6 for a description of the classification of indicators based on data availability).

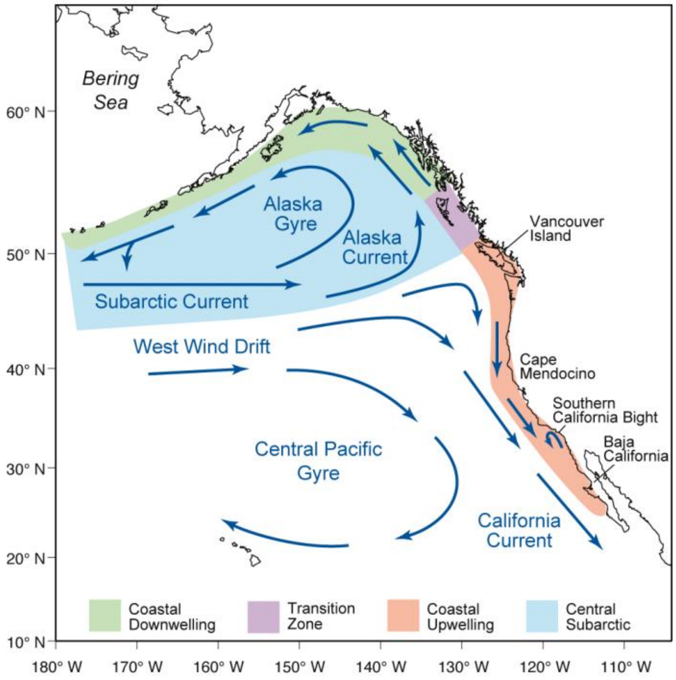
Temperature and precipitation patterns for much of California, including the cool wet winters and warm dry summers flavored with coastal fog are determined largely by ocean conditions. In turn, ocean conditions are linked to atmospheric processes, particularly the intensity and timing of winds.

Four ocean-related indicators are discussed in this document: two indicators of impacts on physical systems: (1) ocean temperature, and (2) oxygen concentrations on California Current; and two indicators of impacts on biological systems: (1) copepod populations, and (2) Cassin's auklet populations. These reflect emerging scientific information of climate variability in the California coastal ocean.

The California Current

The principal ocean currents affecting the coastal waters of California come from the west. The West Wind Drift flows eastward and bifurcates as it nears the coast with the broad southward-flowing current called the California Current (see figure to the right).

The California Current transports relatively cool, low salinity (from polar ice melt), and nutrient-rich water from sub-Arctic regions to the California coast. It contains a different composition of plant and animal species than the more sub-tropical waters in the region.



Source: J.A. Barth, Oregon State University, 2007

Upwelling near the California Coast

During the spring and summer, strong local coastal winds from the northwest (associated with the atmospheric high–pressure system) run parallel to the shore and drive surface waters away from the coast. These waters are replaced by deeper cooler water "upwelled" onto the continental shelf (see figure on the next page). The upwelling of these nutrient-enriched waters closer to the surface enhances growth and photosynthesis by phytoplankton, the cornerstone of the marine food web. This results in tremendous biological productivity and supports an abundance of valuable fisheries such as sardine, market squid and salmon, and a variety of marine mammals, turtles, and birds (Smith, 1968; Parrish et al., 1981; Huyer, 1983).

Source: NOAA, Cordell Bank National Marine Sanctuary, 2007

Vertical stratification, a measure of the increase in water density with depth, influences upwelling. When waters are more highly stratified -- due to a greater contrast between the less dense, warmer surface water and the denser, cooler deep water – more wind energy is required to mix the layers. Weaker winds and increased heating of surface waters – a consequence of global warming – will lead to greater stratification, reduced upwelling and lower biological productivity (Roemmich and McGowan, 1995).

Less upwelling also occurs as the movement of the California Current decreases due to wind and climate changes. Consequently, the coastal waters will consist of relatively more subtropical water carrying less dissolved oxygen (Stramma et al., 2008). As discussed in the indicator of “Oxygen concentrations in the California Current,” there is evidence that shallow oxygen-deficient zones have developed, reducing the depth of favorable habitat for many marine organisms (Bograd, 2008).

Climate variability and ocean conditions

Important cyclical climate phenomena, including the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), influence the California Current and many physical and biological changes in the Pacific Ocean.

El Niño-Southern Oscillation

El Niño (Philander, 1990) is an oscillation of the ocean-atmosphere system in the tropical Pacific that affects global weather. El Niño events occur irregularly at intervals of two to seven years, with the strongest events occurring about once per decade, the last being 1997-98. They typically last 12 to18 months, peaking along the coasts of North and South America around December (hence the name El Niño, Spanish for The Child, in reference to Christmas).

El Niño events often produce heavy rains and floods in California and reduced upwelling. The negative phase of ENSO, called La Niña, occurs when the trade winds blow unusually hard and the ocean temperatures become colder than normal.

Pacific Decadal Oscillation (PDO)

The PDO represents a much longer-scale (multi-decadal) phenomenon and mainly affects Washington, Oregon, and northern California. The PDO is based on ocean surface temperature patterns for the North Pacific (Mantua et al., 1997). Typically, the phases of the PDO, referred to as regimes, represent relatively stable ocean states, separated by sharp and rapid transitions.

Scientists are working to understand the mechanisms responsible for the natural decadal variability represented by the PDO. The positive phase of the PDO is associated with warmer than normal ocean temperatures off California and generally lower biological productivity, as seen in the ocean indicators. Different dominant assemblages of fish and other marine species characterize the phases of the PDO (Peterson and Schwing, 2003).

The PDO appears to have considerable influence on terrestrial systems as well. Warm phases of the PDO are correlated with North American temperature and precipitation anomalies similar to El Niño, including warm and wet conditions for most of California, and increases in the volume of Sierra snowpack and flood frequency (Cayan, 1996). Over the western U.S., the warm phase also corresponds with periods of reduced forest growth (Mote et al., 1999; Peterson and Peterson 2001), more extensive wildfires (Mote et al., 1999), and disease outbreaks.

Climate change effects on the ocean

Warmer air and ocean temperatures, especially in summer, are projected to contribute to greater ocean stratification, weaker upwelling, a lower rate of biological productivity, a northward shift in the distribution of subtropical fisheries, and the expansion of invasive and exotic species.

Changes in storm patterns and precipitation are likely to cause warmer and wetter winters, greater freshwater discharge into the coastal ocean, coastal flooding, stronger and more frequent storms, and even hurricanes. These changes could reduce coastal water quality, and increase toxic algal blooms and other ocean-borne health hazards. Higher coastal sea level could displace intertidal species and reduce the area of coastal and estuarine wetlands that are crucial nursery grounds for many marine species.

A more detailed discussion of the ocean and climate change can be found in Appendix A.

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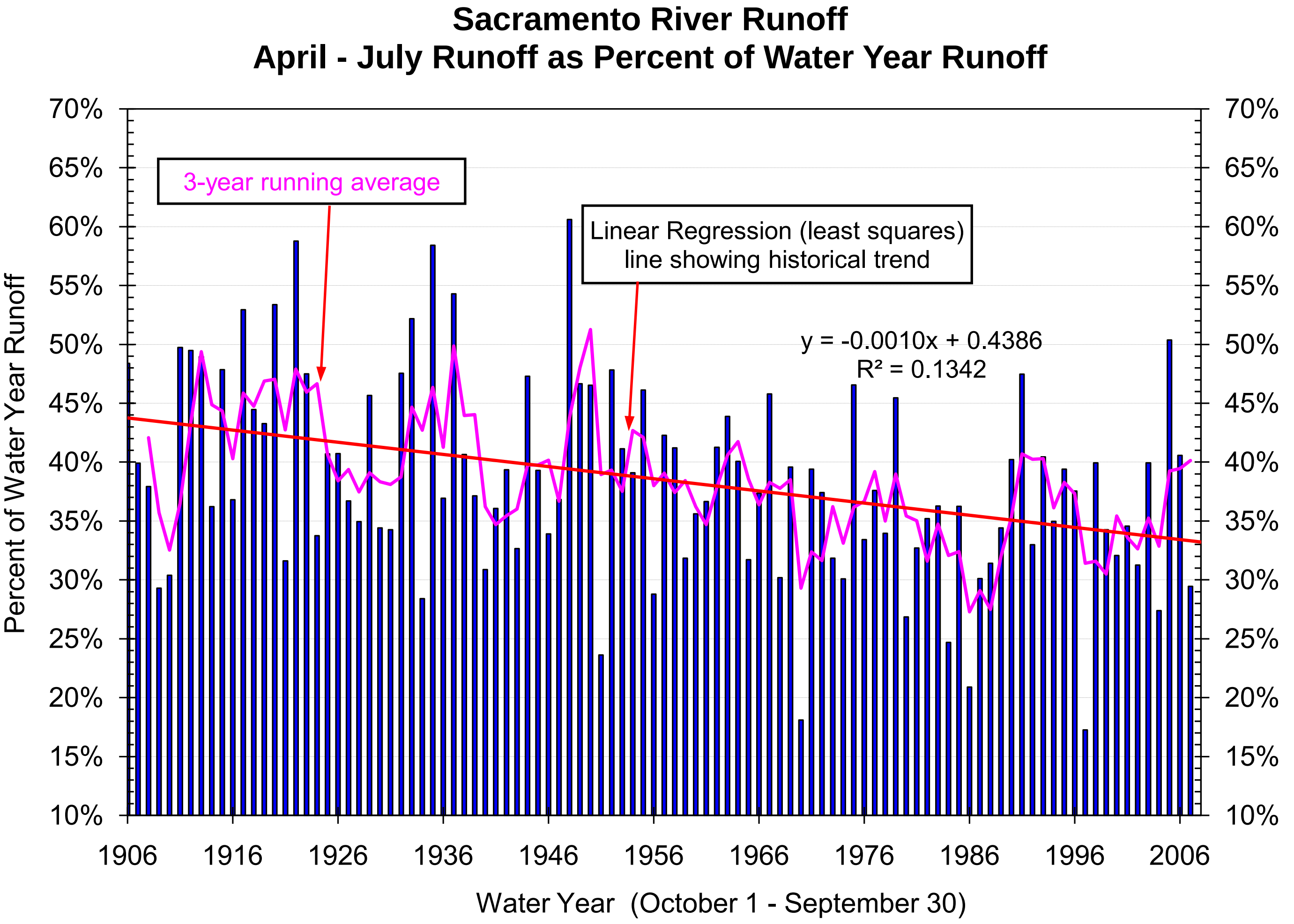
Impacts on physical systems

ANNUAL SIERRA NEVADA SNOWMELT RUNOFF

Spring runoff in California has declined over the past century.



Source: DWR, 2008

What is the indicator showing?

The percentage of annual runoff fraction during the spring snowmelt period of the Sacramento River has decreased by 10 percent since 1906.

Why is this indicator important?

The Sacramento River system is the sum of the estimated unimpaired or natural runoff of the Sacramento River and its major tributaries, the Feather, Yuba and American Rivers. The fraction of the annual stream discharge that occurs from spring and early summer snowmelt, computed as the percentage of April through July discharge to each water year's (October through September) annual total, provides a measure of temperature-related runoff patterns. Large accumulations of snow occur in the Sierra Nevada and southern Cascade Mountains from October to March. Each winter, at the high elevations, snow accumulates into a deep pack, preserving much of California's water supply in cold storage. Spring warming causes snowmelt runoff, mostly during April through July. If the winter temperatures are warm, more of the precipitation falls as rain instead of snow, and water directly flows from watersheds before the spring snowmelt. Other factors being equal, there is less buildup of snow pack; as a result, the volume of water from the spring runoff is diminished. Lower water volumes of the spring snowmelt runoff may indicate warmer winter temperatures or unusually early warm springtime temperatures.

An increase in the portion of watershed precipitation falling as rain rather than snow in the winter results in higher flood risks and reduced snow-related recreational opportunities in the mountains. Less spring runoff can reduce the amount of potential summer water available for the state's water needs and hydroelectric power production. Lower runoff volumes can also impact recreation opportunities, and impair cold water habitat for salmonid fishes (Roos, 2000).

What factors influence this indicator?

The warming of global climate would affect the yearly ratio of rain to snow, as well as mountain snow level elevations. The warmer the storm temperature is, the higher the elevation at which snow falls and accumulates. Higher elevations of the snow line mean reduced snow pack and lower spring water yields.

Snowmelt and runoff volume data can be used to document changes in runoff patterns. These changes are likely due to increased air temperatures and climate changes. Other factors, such as the Pacific Decadal Oscillation (North Pacific Ocean temperature patterns) and, possibly air pollution, probably contribute to the patterns observed.

During the 20th century, the fraction of annual unimpaired runoff that occurs from April through July, represented as a percentage of total water year runoff from the accumulated winter precipitation in the Sierra Nevada, has been decreasing. "Unimpaired" runoff refers to the amounts of water produced in a stream unaltered by upstream diversions, storage, or by export or import of water to or from other basins. This decreased runoff was especially evident after mid-century; since then the April through July runoff percentage has declined by about ten percent. Most of the change took place after 1950 and the recent two decades seem to indicate a flattening of the percentage decrease. There is no significant trend in total water year runoff, just a change in timing of runoff.

Technical Considerations:

Data Characteristics

The California Cooperative Snow Surveys Program of the California Department of Water Resources (DWR) collects the data. Runoff forecasts are made systematically, based on historical regression relationships between the volume of April through July runoff and the measured snow water content, precipitation, and runoff in the preceding months (Roos, 1992). The snow surveys program began in 1929.

Related snow pack information is used to predict how much spring runoff to expect for water supply purposes. Each spring, about 50 agencies, including the United States Departments of Agriculture and Interior, pool their efforts in collecting snow data at about 270 snow courses throughout California. A snow course is a transect along which snow depth and water equivalent observations are made, usually at ten points. The snow courses are located throughout the state from the Kern River in the south to Surprise Valley in the north. Courses range in elevation from 4,350 feet in the Mokelumne River Basin to 11,450 feet in the San Joaquin River Basin.

Since the relationships of runoff to precipitation, snow, and other hydrologic variables are natural, it is preferable to work with natural or unimpaired runoff. The spring runoff is calculated purely from stream flow. These are the amounts of water produced in a stream unaltered by upstream diversions, storage, or by export or import of water to or from other basins. To get unimpaired runoff, measured flow amounts have to be adjusted to remove the effect of man-made works, such as reservoirs, diversions, or imports (Roos, 1992). The water supply forecasting procedures are based on multiple linear regression equations, which relate snow, precipitation, and previous runoff terms to April-July unimpaired runoff.

Major rivers in the forecasting program include the Sacramento, Feather, Yuba, American, San Joaquin, Merced, Tuolumne, Stanislaus, and Kings on the western slopes of the Sierra, and the Truckee, Walker, Carson and Owens on the eastern slopes. Spring runoff percentages have declined throughout much of the mountain range:

River Runoff	***Percent Decline in the 20th Century***
Sacramento River system	10
San Joaquin River system	7
Kings	6
Kern	10
Trinity	11
Truckee	15
Carson and Walker	5

Strengths and Limitations of the Data

River runoff data have been collected for almost one century for many monitoring sites. Stream flow data exist for most of the major Sierra Nevada watersheds because of California’s dependence on their spring runoff for water resources and the need for flood forecasting. The April to July unimpaired flow information represents spring rainfall, snowmelt, as adjusted for upstream reservoir storage calculated depletions, and diversions into or out from the river basin. Raw data are collected through water flow monitoring procedures and used along with the other variables in a model, to calculate the unimpaired runoff of each watershed.

Over the years, instrumentation has changed and generally improved; some monitoring sites have been moved short distances to different locations. The physical shape of the streambed can affect accuracy of flow measurements at monitoring sites, but most foothill sites are quite stable.

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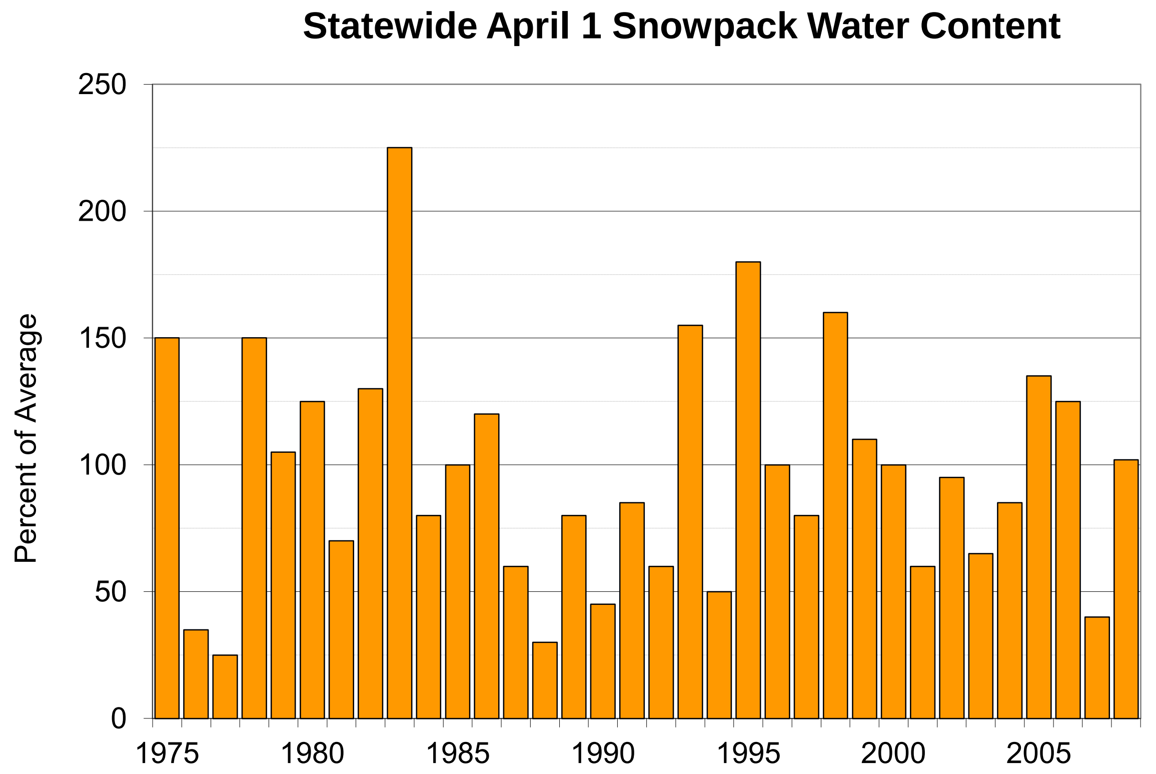
For more information, contact:

Maurice Roos
Department of Water Resources
Division of Flood Management
3310 El Camino Avenue
P.O. Box 219000
Sacramento, California 95821-9000
(916) 574-2625
mroos@water.ca.gov

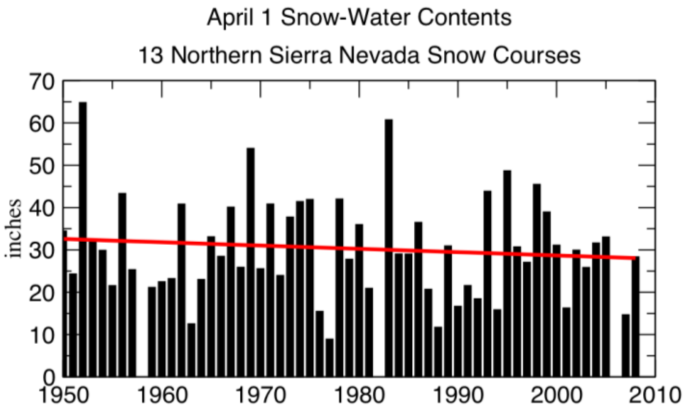
Impacts on physical systems

SNOW-WATER CONTENT

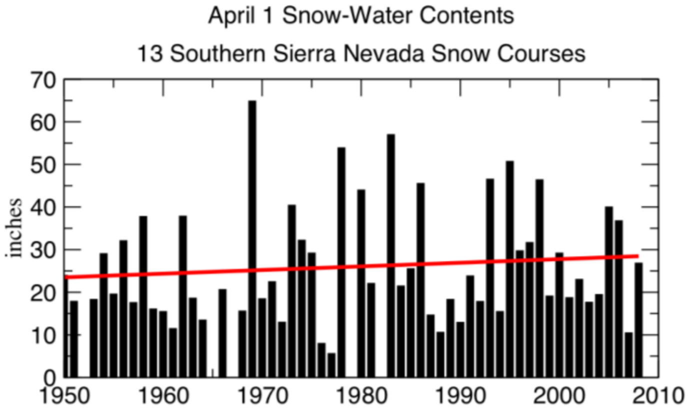
The average total water stored in the state's snowpacks on April 1 of each year has stayed roughly the same in recent decades for the state as a whole, but has declined in the northern Sierra Nevada and increased in the southern Sierra Nevada.



Source: DWR, 2008



Source: DWR, 2008



Source: DWR, 2008

What is the indicator showing?

The first graph presents time series data for April 1 snowpack water content averaged from measurements taken at stations in the Trinity Alps south to the Kern River basin. Since 1985, snow-water content statewide has ranged from about 20 percent of average water content in the severe drought year of 1977, to over 220 percent content in the very wet El Niño year of 1983. No overall trend in the statewide averages is indicated during the past several decades.

By contrast, snow-water contents have trended towards less water stored in snowpacks in the Northern Sierra Nevada, and towards more water stored in snowpacks in the Southern Sierra Nevada during the past several decades, as shown by two additional graphs. April 1 snow-water contents have declined by about 15 percent in the northern Sierra Nevada since 1950, while increasing by about 15 percent in the southern Sierra Nevada. Together, the decreases in the north and increases in the south have combined to yield little or no net change in the statewide snow-water content averages.

Snow-water content is the amount of water that is stored in the snowpack above a point on the ground at any given time. It is measured by weighing the mass, traditionally, of a core of snow — from snow surface to soil — collected by an observer in the field or, more recently, of the snow laying on top of a large scale, called a snow pillow. In either case, the weight of snow is a measure of how much liquid water would be obtained by melting the snow over a given area. Thus snow-water content is a measure of how much water is locked up in the snowpacks at a given location, water that will mostly be available to run off or percolate into soils once the snow is melted in spring and summer. Snow-water content is usually measured in units of inches of water contained in the snow.

Traditionally, a reasonable rule of thumb has been that California's snowpacks are thickest and contain the most water by about April 1 of each year. From year to year and place to place, the date of maximum snow-water contents varies, but April 1 has usually been used to estimate how much water is stored in the State's snowpacks for release (by melting) later in the year. As the climate warms, the dates of maximum snowpack are generally predicted to come earlier in the year; however, continued monitoring of the April 1 snowpack should provide the data needed to determine how much total warm-season water supplies from snowmelt will have changed.

Why is this indicator important?

By April 1, California's snowpacks have historically stored about 15 million acre-feet of water. This amount of naturally occurring water storage has been an integral part of California's water-supply systems. The combined storage capacities of the State's major, front-range reservoirs (such as Don Pedro, Oroville, and Friant) are between 20 and 25 million acre-feet. Snow has traditionally added about 40 percent to the reservoir capacity available to water managers in the state, carrying water over from the winter wet seasons to the summer dry seasons that typify California's climate.

Notably, not all the range-front reservoir capacity is available in wintertime, so that snowpacks are all the more important. California receives its largest and most dangerous storms in wintertime, and its most devastating floods have occurred during that season. In order to balance flood-risk management and water-supply considerations, California's water managers have developed a strategy of maintaining empty space in the major reservoirs during winter, so that flood flows can be captured or at least reduced when necessary. By about April 1, when most of the winter storms stop reaching California, flood risks generally decline considerably. At this time, reservoir managers change strategies and instead capture as much streamflow as possible to fill flood-control spaces so that as much water as possible will be in the reservoirs by summer when water demands are highest. This strategy works primarily because, during winter, the State's snowpacks are holding copious amounts of the winter's precipitation in the mountain watersheds, only releasing most of it to the manmade reservoirs after about April 1.

To the extent that climate change depletes the State's snowpacks in the future (Knowles and Cayan, 2004), this historical flood- and water-management strategy will be severely challenged. Thus, it is important to monitor whether the State's snowpacks are declining, increasing, or staying the same.

What factors influence this indicator?

April 1 snow-water contents are determined by winter and spring precipitation totals and air temperatures. To a lesser extent, they may be influenced by the amount of solar radiation that falls on the snowpacks in each season, which, in turn, depends on cloudiness and timing of the beginning of the snowmelt seasons (Lundquist and Flint, 2006). Under climate change, any of these climatic influences may change, with warming trends very likely to lead to depletions in the amount of snowpack available (if precipitation does not increase too markedly; e.g., Knowles and Cayan, 2004). If precipitation increases, snow-water contents could increase in those areas that are still cold enough to receive snowfall (above the retreating snowlines); if precipitation decreases, snow-water contents may be expected to decline even faster than due to warming alone. Increases in cloudiness (decreases in solar radiation on the snowfields) would tend to result in less wintertime snowmelt and thus more snow-water content left by April 1 (the opposite would occur if cloudiness declines in the future).

The declines in snow-water contents in the north are part of a much broader pattern of declining snowpacks across the western United States – a pattern that has been associated with springtime warming trends and earlier snowmelt seasons in recent years by several different scientific studies (e.g., Mote, 2003; Barnett et al., 2008). The increases in snowpacks in the southern Sierra Nevada are part of a more localized pattern, associated with the proliferation of El Niño climate conditions since about the mid-1970s (e.g., McCabe and Dettinger, 2002). During El Niño winters, the southwestern United States, including the southern Sierra Nevada, are typically wetter than normal (Cayan and Webb, 1992), so that snowpacks are consequently thicker and store more water by April. This southern trend towards more precipitation has thus far been a larger influence on snowpack totals in the south than has the warming trend and its attendant earlier snowmelts.

Technical Considerations:

Data Characteristics

As indicated previously, snow-water content has traditionally been measured by weighing cores of snow pulled from the whole depth of the snowpack at a given location. Since the 1930s, within a few days of the beginning of each winter and spring month, snow course measurements have been performed by skiing or flying to remote locations and extracting 10 or more cores of snow along ¼ mile-long pre-marked “snow course” lines on the ground. The depth of snow and the weight of snow in the cores is measured, the weights are converted to a depth of liquid water that would be released by melting that weight of snow, and the results from all the measurements at the snow course are averaged to arrive at estimates of the snow-water content at that site.

The statewide snow-water content values plotted above are averages of snow-water content measurements made at 104 snow courses from the Trinity Alps to the Kern River, with 27 courses included from the Trinity area south to the Feather and Truckee basins, 44 courses from the Yuba and Tahoe basins to the Merced and Walker basins, and 33 courses from the San Joaquin and Mono basins south to the Kern basin. A list of the snow courses used and the most recent summary statistics are available at http://cdec.water.ca.gov/cgi-progs/snow/DLYSWEQ . Data from 13 of the most serially complete (fewest missing years of data) snow courses in the Sacramento, Feather, Yuba, and American River basins were used to estimate the northern Sierra time series shown; similarly, 13 of the most serially complete snow courses in the Upper San Joaquin, Kings, and Kern River basins were compiled to form the southern Sierra Nevada series shown.

The many snow courses that monitor California’s snowpacks are coordinated by the California Cooperative Snow Surveys program at the Department of Water Resources. The resources, including personnel, transportation and funding, necessary to keep these long-term data-collection efforts come from a variety of sources, including State, Federal, and local agencies. Data are routinely reported and summarized at the Cooperative Snow Survey’s website (http://136.200.137.25/snow/) and through the California Data Exchange Center (CDEC).

Strengths and Limitations of the Data

The measurements are relatively simple and the measurement methods have not changed during all the decades since monitoring started. Averaging of the 10 or more measurements at each course does yield relatively accurate and representative results. During the past two decades, continuous snow-measurement instrumentation has been established at many of the snow courses, measuring the weight of snow on the ground (along with several meteorological variables) with a snow pillow. Snow pillows are large (12 feet by 12 feet), flat, flexible tanks filled with denatured alcohol or other liquids that do not freeze at winter temperatures, buried just below the ground surface. As snow piles up on the pillows, it squeezes the tanks and liquids they contain, raising the pressure in the tanks, and that pressure change is used to determine the weight of snow on the tank and ground. The availability of continual snow weight, and thus snow-water content, measurements at the snow courses allows more snow-water content information of greater time resolution to be collected, and serves as a valuable check on the representativeness and accuracy of the snow-course measurements, which will continue to be made for the foreseeable future.

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For more information, contact:

Michael Dettinger
California Applications Program
& California Climate Change Center
Scripps Institution of Oceanography
UCSD, Dept 0224
9500 Gilman Drive
La Jolla, CA 92093-0224
(858) 822-1507
mdettinger@ucsd.edu

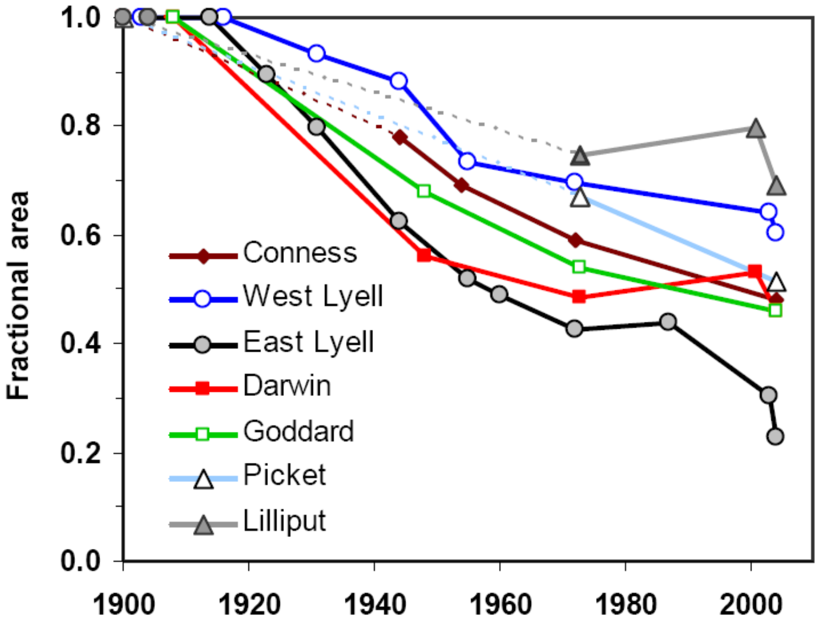
Frank Gehrke, Chief
California Cooperative Snow Surveys
Department of Water Resources
Joint Operations Center
P.O. Box 219000
Sacramento, CA 95821-9000
(916) 574-2635
gridley@water.ca.gov

Impacts on physical systems

GLACIER CHANGE

Glaciers in the Sierra Nevada have decreased in area over the past century.

Change in Surface Area, Sierra Nevada Glaciers



Source: Basagic, 2008

NOTE: Dashed lines represent assumed change for glaciers lacking early 1900s photographic evidence.

Lyell Glacier, East (left) and West (right) lobes

1903

G. K. Gilbert

2004

H. Basagic

Darwin Glacier

1908

G. K. Gilbert

2004

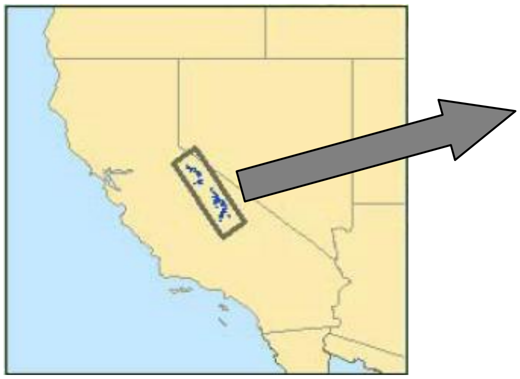
H. Basagic

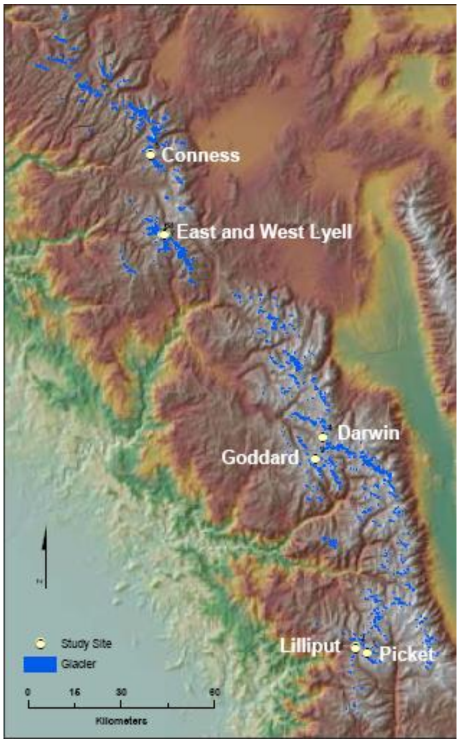
What is the indicator showing?

The surface area of seven Sierra Nevada glaciers (see map, below) has decreased over the past century (Basagic, 2008). The graph shows changes in area relative to 1900. In 2004, the area of these seven glaciers ranged from 22 to 69 percent of their 1900 area.

The photographs show change in the Lyell and Darwin glaciers over the past century. Losses in both glacier area and volume over time are evident from the photographs. Additional photographs can be viewed at the "Glaciers of the American West" web site, http://www.glaciers.us.

Maps showing the Sierra Nevada glaciers (below), and the seven glaciers studied (right).





Glacier locations:
Conness: Inyo National Forest, east of Yosemite National Park
Lyell: Headwaters of Tuolumne River, in eastern Yosemite
Darwin and Goddard: Northern Kings Canyon National Park
Lilliput and Picket: Sequoia National Park

Source: Basagic, 2008

Why is this indicator important?

Glaciers are important indicators of climate change. Over the twentieth century, with few exceptions, alpine glaciers have been receding throughout the world in response to a warming climate. Historical glacier responses preserved in photographic records, and prehistoric responses preserved as landscape modifications are important records of past climates in high alpine areas where few other climate records exist.

Glaciers are also important to alpine hydrology. They begin to melt most rapidly in late summer after the bright, reflective seasonal snow disappears, revealing the darker ice beneath. This causes peak runoff to occur in late summer when less water is available and demand is high. Glacier shrinkage reduces this effect, resulting in earlier peak runoff and drier summer conditions. These changes are likely to have ecological consequences for flora and fauna in the area that depend on available water resources. Finally, glacier shrinkage is an important contribution to global sea level rise.

What factors influence this indicator?

A “glacier,” by definition, is a mass of perennial snow or ice that moves. As such, glaciers are a product of regional climate, responding to the combination of winter snow and spring/summer temperatures. Winter snow fall nourishes the glaciers, and spring/summer temperatures melt the ice and snow. Summer air temperature affects the rate of snow and ice melt. Winter temperature determines whether precipitation falls as rain or snow and therefore affects snow accumulation and glacier mass gain. The greater the winter snowfall, the healthier the glacier. Climate data for the Sierra Nevada show a 0.6^{o}C increase in mean annual air temperature over the past century. Seasonal spring, summer and winter mean temperatures likewise increased, with spring mean temperatures showing the greatest change (+1.8^{o}C). The glacier retreat (i.e., decrease in size) in the Sierra Nevada occurred during extended periods of above average spring and summer temperatures. Winter snow fall appears to be a less important factor.

Following a cool and wet period in the early part of the century during which glacier area was constant, the Sierra Nevada glaciers began to retreat rapidly with warmer and drier conditions in the 1920s. The glaciers ceased retreating, while some glaciers increased in size (or “advanced”) during the wet and cool period between the 1960s and early 1980s with below average temperatures. By the late 1980s, with increasing spring and summer temperatures, glacier retreat resumed, accelerating by 2001. Hence, the timing of the changes in glacier size appears to coincide with changes in air temperatures. In fact, glacier area changes at East Lyell and West Lyell glaciers were found to be significantly correlated with spring and summer air temperatures.

It is interesting to note that this pattern of change in the Sierra Nevada glaciers – that is, a decrease in area, followed by an increase (or “advance”), then a retreat -- is similar to that of glaciers throughout the Western United States and the world. Based on their assessment of studies of glaciers in various parts of the world, the Intergovernmental Panel on Climate Change concluded that human-induced warming has likely contributed substantially to widespread glacier retreat during the twentieth century (Intergovernmental Panel on Climate Change (IPCC), 2007).

While each of the Sierra Nevada study glaciers has resumed retreat since the 1980s, a unique response was observed for Mount Shasta, where glaciers advanced from 1995 to 2003. An analysis of climate data and historical records of glacier extent over the past century showed the latter to be affected more by precipitation than by temperature. There has been an increase in the magnitude and frequency of warm, heavy precipitation-bearing storms driven primarily by inter-decadal swings in precipitation linked to Pacific Ocean climate with the Pacific Decadal Oscillation. Such storms result in an increase in rainfall, as opposed to snow, at low elevations, but an increase in snow accumulation at higher elevations (Howat et al., 2007). Despite warmer temperatures during the past few decades, Mount Shasta’s ice volume has remained relatively stable and its glaciers have continued to advance due to a large increase in winter snow accumulation.

As can be seen from the graph, the seven glaciers studied have all decreased in area. However, the magnitude and rate of change are variable, suggesting that factors other than regional climate influenced these changes. One of these factors is glacier geometry: A thin glacier on a flat slope will lose more area compared to a thick glacier in a bowl-shaped depression, even if the loss of mass was the same. In addition, local topographic features, such as headwall cliffs, influence glacier response through shading solar radiation, and enhance snow accumulation on the glacier through avalanching from the cliffs.

A glacier gains or loses mass through climatic processes, then after some lag time responds by either advancing or retreating. The area changes observed in the photographs of the study glaciers were instigated by climatic changes, but modified by the dynamics of ice flow. Hence, glacier change is a somewhat modified indicator of climate change, with local variations in topography and climate either enhancing or depressing the magnitude of change so each glacier's response is somewhat unique.

Technical Considerations:

Data Characteristics

To quantify the change in glacier extent, seven glaciers in the Sierra Nevada were selected based on the availability of past data and location: Conness, East Lyell, West Lyell, Darwin, Goddard, Lilliput, and Picket glaciers. Glacier extents were reconstructed using historical photographs and field measurements. Aerial photographs were scanned and imported into a geographic information system (GIS). Only late summer photographs, largely snow free, were used in interpretation of the ice boundary. The historic glacier extents were interpreted from aerial photographs by tracing the ice boundary. Early 1900 extents are based on ground-based images and evidence from moraines. To obtain recent glacier areas, the extent of each glacier was recorded using a global positioning system (GPS) in 2004. The GPS data was post processed (2-3m accuracy), and imported into the GIS database. Glacier area was calculated within the GIS database.

Strengths and Limitations of the Data

The observation of tangible changes over time demonstrates the effects of climate change in an intuitive manner. This indicator relies on data on glacier change based on photographic records, which are limited by the availability and quality of historical photographs. Increasing the number of study glaciers and the interval between observations would provide a more robust data set for analyzing statistical relationships between glacier change and climatological and topographic parameters. Additionally, volume measurements would provide valuable information and quantify changes that area measurements alone may fail to reveal.

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For more information, contact:

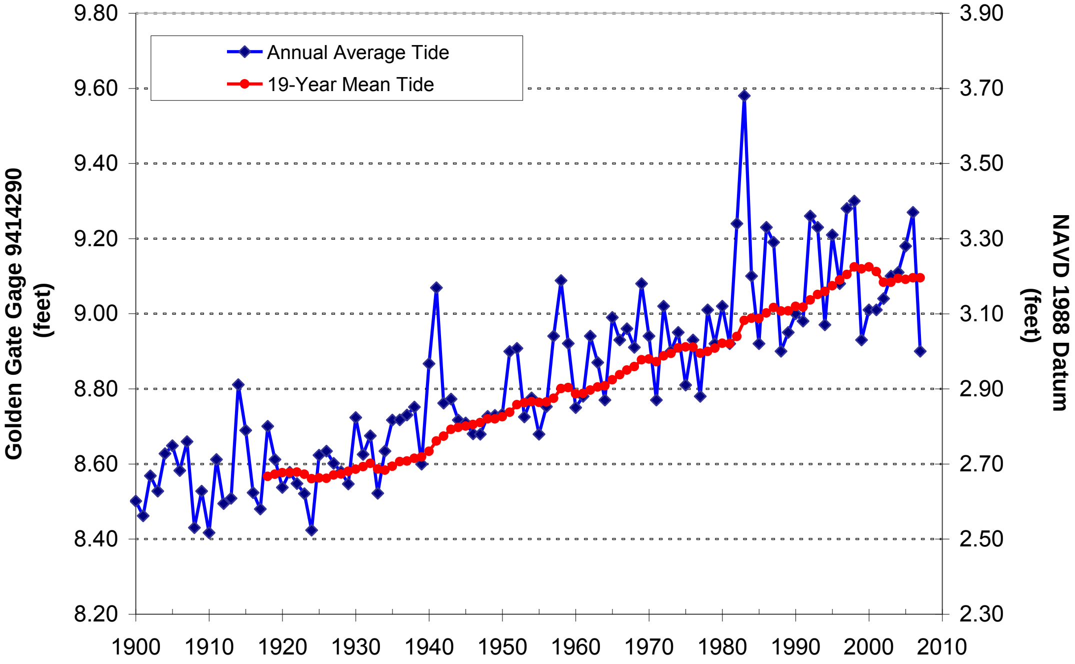
Portland State
UNIVERSITY
Andrew G. Fountain and Hassan J. Basagic
Department of Geology
Portland State University
P. O. Box 751
Portland, OR 97207-0751
andrew@pdx.edu
(503) 725-3386
www.glaciers.us/

Impacts on physical systems

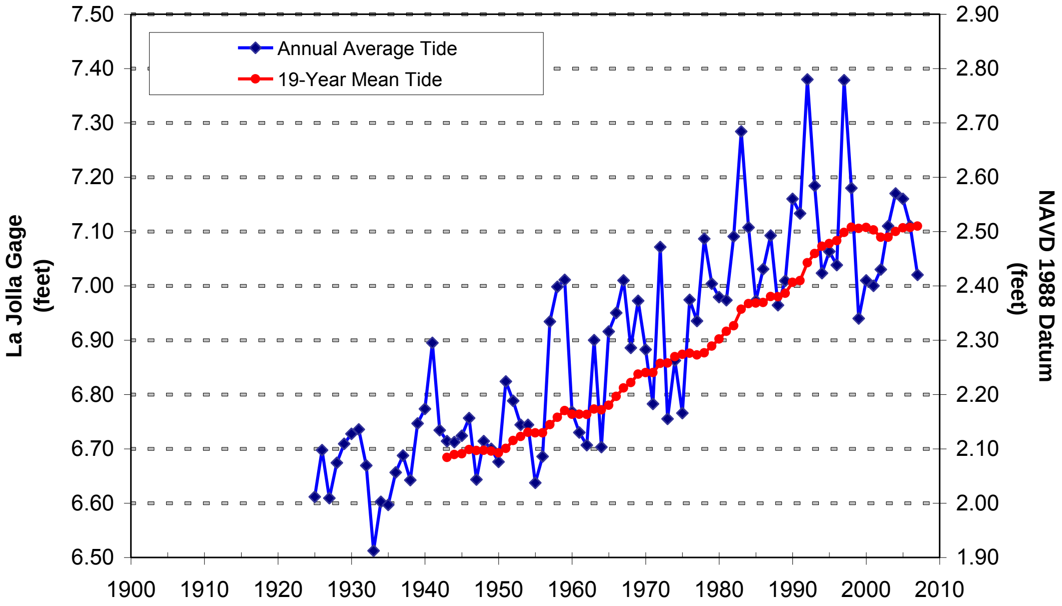
SEA LEVEL RISE

Sea levels have increased over the past century.

Golden Gate Annual Average and 19-Year Mean Tide Levels



La Jolla Annual Average and 19-Year Mean Tide Levels



Source: Maury Roos, Binta Coleman, DWR

What is the indicator showing?

Sea levels have risen at two tide gage locations along the California coast.

Why is this indicator important?

Sea level rise provides a physical measure of possible oceanic response to climate change. Average global sea level has risen between five to nine inches during the 20th century (IPCC, 2007), nearly one-tenth of an inch each year. The indicator shows the rising trend in sea level measured at two California stations: San Francisco and La Jolla. While sea level data from only two California stations are presented, long-term data from 10 of 11 California stations show increases in sea level. Hence, while the rates of increase vary, sea level is increasing almost everywhere in California (Flick, 1999).

The rise in global sea level is attributed to the thermal expansion of ocean water and the melting of mountain glaciers and ice sheets around the globe. At the current rate of rise, the seas could rise another half foot over the next 50 years (IPCC, 2007). However, sea level rise is not a new phenomenon, having been a major natural component of coastal change throughout time. The concern is that with increased global warming and melting of ice sheets on Greenland and West Antarctica the rate of change may increase.

Sea level rise and storm surges could lead to flooding of low-lying areas, loss of coastal wetlands such as the San Francisco Bay Delta, erosion of cliffs and beaches, saltwater contamination of groundwater aquifers and drinking water, and impacts on roads, causeways, storm drains and bridges. California's hundreds of miles of scenic coastline contain ecologically fragile estuaries, expansive urban centers, and fisheries that could be impacted by future changes in sea level elevation.

What factors influence this indicator?

Along California's coast, sea level already has risen by three to nine inches over the last century (three inches at Los Angeles, eight inches at San Francisco, and an estimated nine inches at La Jolla near San Diego), and it is likely to rise by another 0.6 to about 2.5 feet by 2100 (IPCC, 2007). Differences in sea level rise along the coast can occur because of local geological forces, such as land subsidence and plate tectonic activity. Crescent City, for example, on the far North Coast shows a decrease of about 2 inches over the century (the land has risen relative to the sea).

The rise in sea level is likely associated with increasing global temperatures. A major component of the rise is that global warming is causing melting of mountain glaciers and ice caps. A second major component, based on results from modeling, is warming of the ocean water which causes a greater volume of sea water because of thermal expansion. There has been a widespread retreat of mountain glaciers in non-polar regions during the past 100 years. There is a trend for reduced Arctic sea-ice in the late summer, and there may be a trend of Antarctic sea-ice reductions on the fringes of that continent. Melting of sea ice itself does not result in higher sea levels, but it may accelerate loss of land-based ice.

The earth goes through cycles of warming and cooling, called ice ages, about every 100,000 years. The colder glacial cycles occur when the earth is in an oval elliptical orbit and farther from the sun. Because of the cooling, water from the oceans and precipitation forms ice sheets and glaciers. Much of the water is stored in the polar ice caps and in land-bound glaciers. However, during the earth's shorter, circular orbit, it is closer to the sun, warms up, and water flows from melting glaciers to the oceans, driving up sea level. These warming interglacial periods last about 10,000 years. We are about two-thirds of the way through a warming trend now. During the last interglacial period, sea level rose about 20 feet above where it is today (IPCC, 2001). Global warming studies predict that global sea level will rise at an accelerated rate, much beyond that seen in prehistoric "natural" cycles of warming and cooling evidenced by geologic data.

Technical Considerations:

Data Characteristics

The San Francisco data are obtained from the Golden Gate tide gage, and the La Jolla data from a gage at the Scripps Institution of Oceanography pier. The San Francisco record begins in 1855 and represents the longest continuous time series of sea level in North America (Flick, 1998). The record at San Francisco shows a sea level rise of about 8 inches from 1855 to 2000 with an offset of about 0.1 to 0.2 feet in 1906, the year of the San Francisco earthquake. The rate of rise was quite slow until about the 1920s, but now has been at a rate of about 8 inches per century, with some apparent slowing during the last decade. This agrees with a much broader collection of tide gage data that show that global average sea level rose between five to nine inches during the 20th century. The tide gage record at La Jolla shows an increase in mean sea level of approximately 6 inches in the past 75 years, or looking back, perhaps 9 inches per century. Tide data for these two stations and from other California monitoring stations are posted at the web site of the National Ocean Service of the National Oceanic and Atmospheric Administration.

Monthly or yearly mean sea level statistics are derived by averaging near-continuous water level measurements from tide gauges. Sea level fluctuates at all time scales, but tide gauges remove the effects of waves and other fluctuations shorter than about 12 minutes. Sea levels change with tides, storms, currents, seasonal patterns of warming, and barometric pressure and wind. Ocean levels tend to be higher in the big El Niño years such as 1983 and 1998 and lower in La Niña years like 1998 and 2007.

Strengths and Limitations of the Data

Due to astronomical forces, such as the lunar cycle, it is difficult to isolate possible changes due to global warming by looking at short periods in the sea level tidal record. Monthly mean sea levels tend to be highest in the fall and lowest in the spring, with differences of about 6 inches. Local warming or cooling resulting from offshore shifts in water masses and changes in wind-driven coastal circulation patterns also seasonally alter the average sea level by 8.4 inches (Flick, 1998). For day-to-day activities, the tidal range and elevations of the high and low tides are often far more important than the elevation of mean sea level. Shoreline damage due to wave energy is a factor of wave height at high tide and has a higher impact on the coast than mean sea level rise. The lunar nodal cycle is 18.6 years, which is the reason for plotting the 19 year mean on the charts.

Geological forces such as subsidence, in which the land falls relative to sea level, and the influence of shifting tectonic plates complicate regional estimates of sea level rise. Much of the California coast is experiencing elevation changes due to tectonic forces. Mean sea level is measured at tide gauges with respect to a tide gage benchmark on land, which traditionally was assumed to be stable. This only allows local changes to be observed relative to that benchmark. There are studies in progress that will study the feasibility of monitoring absolute changes in sea level on a global scale through the use of global positioning systems (GPS) satellite altimetry. The GPS may be useful to record vertical land movement at the tide gage benchmark sites to correct for seismic activity and the earth's crustal movements.

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National Ocean Service. Center for Operational Oceanographic Products and Services, National Oceanic and Atmospheric Administration. www.co-ops.nos.noaa.gov.

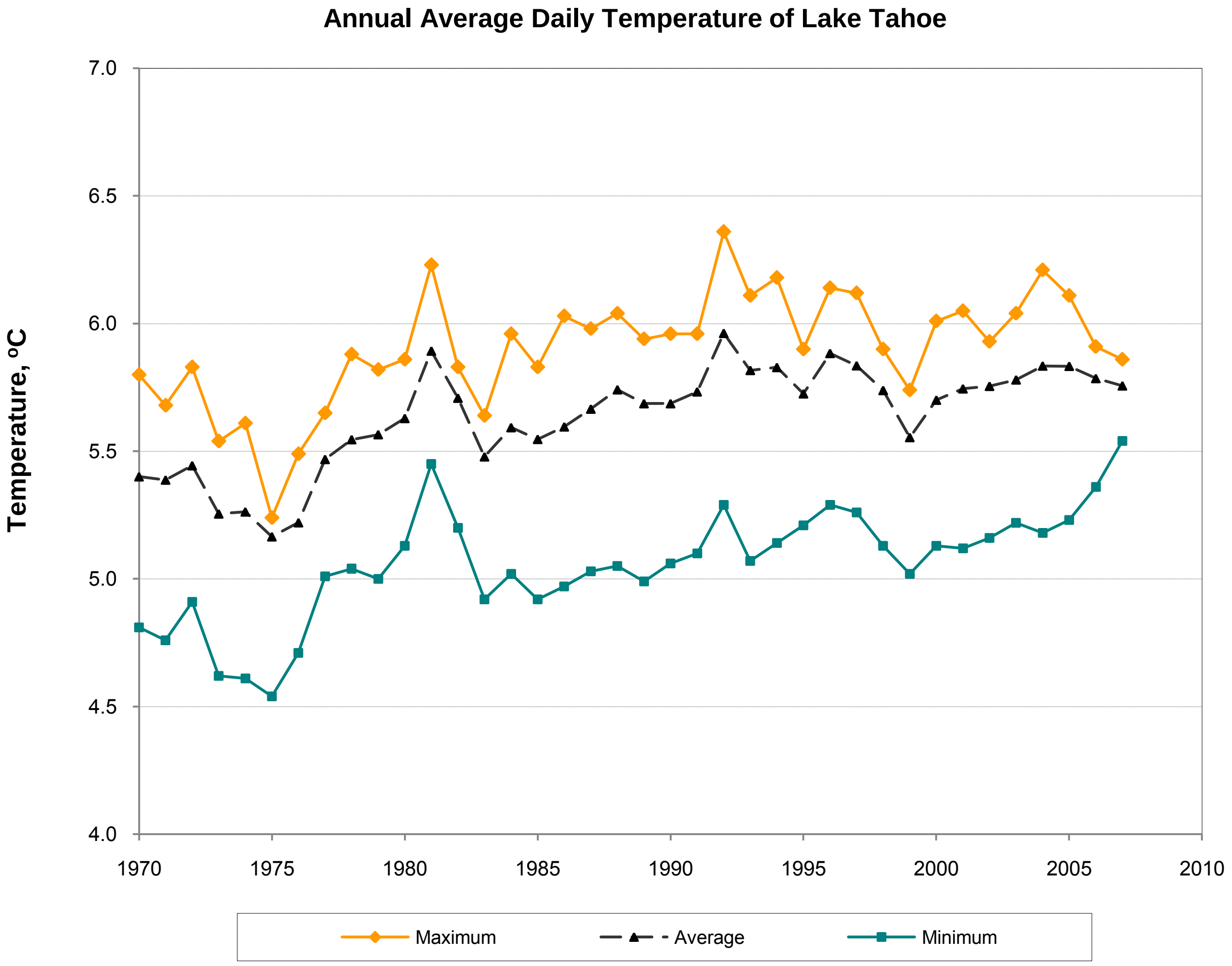
For more information, contact:

Maurice Roos
Department of Water Resources
Division of Flood Management
3310 El Camino Avenue, Suite 200
P.O. Box 219000
Sacramento, CA 95821-9000
(916) 574-2625
mroos@water.ca.gov

Impacts on physical systems

LAKE TAHOE WATER TEMPERATURE

Lake Tahoe's waters have been warming, especially since the mid-1970s.



Source: Coats, UC Davis TERC

What is the indicator showing?

The temperature of Lake Tahoe's waters has been increasing over the past 38 years. The graph above shows the minimum, average and maximum annual-averaged lake temperatures (averaged over the entire lake volume) for each year since 1970. Minimum temperatures have been increasing at a faster rate than either average or maximum temperatures.

Why is this indicator important?

Lake Tahoe is a pristine, crystal-clear high altitude lake, considered one of the jewels of the Sierra. World-renowned for it striking blue color and amazing clarity, its majestic beauty, close proximity to urban areas, and opportunities for hiking, skiing, camping, boating and a host of other recreational activities draw millions of visitors to the area every year (California Tahoe Conservancy, 2008). The lake is designated by the U.S. Environmental Protection Agency as an Outstanding National Resource Water. This special designation under the Clean Water Act affords the highest level of protection, strictly forbidding degradation of water quality. Only two other bodies of water have this designation in the Western United States: Mono Lake in California, and Crater Lake in Oregon (TRPA, 2008).

Lake Tahoe is 35 kilometers long and has a surface area of 500 square kilometers and a total volume of 157 cubic kilometers. Its maximum depth of 501 meters makes it the third deepest lake in North America, and the eleventh deepest lake in the world. The lake never freezes, and the entire water column is oxygenated throughout the year. Thermal stratification usually begins in March or April. The lake mixes completely on average about one year in four.

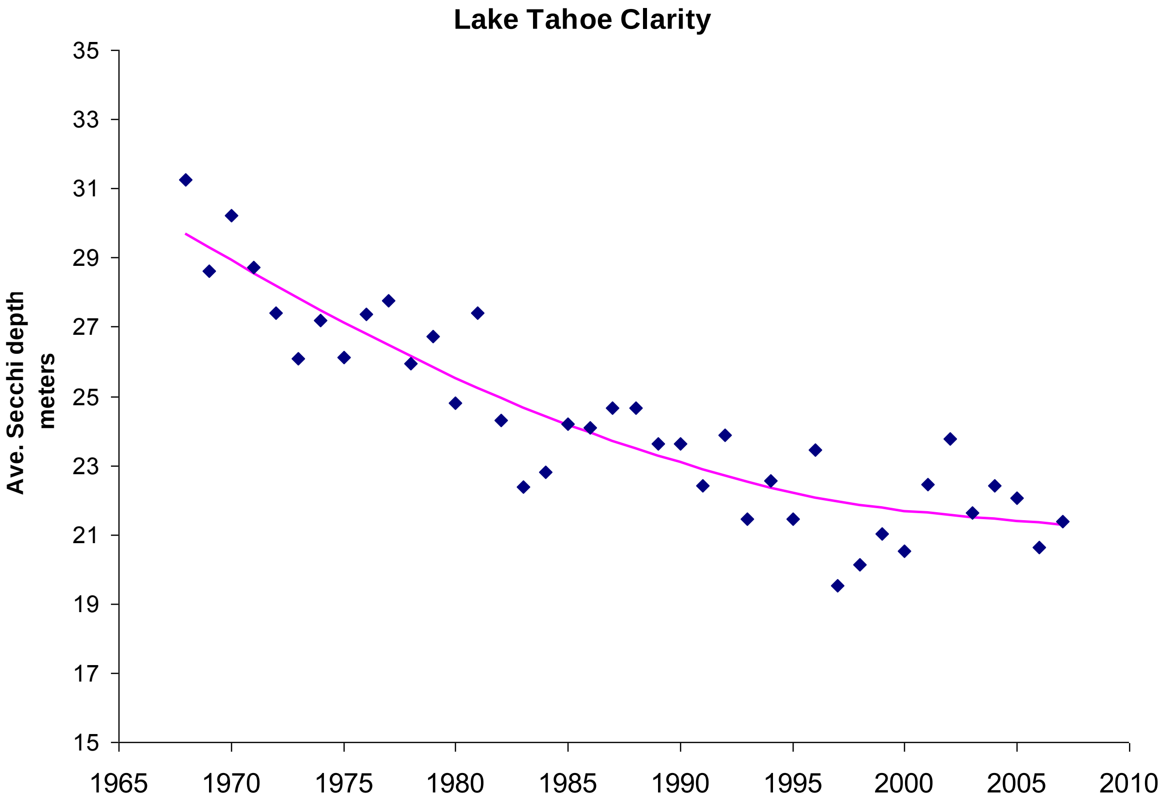
Warmer water temperatures influence the thermal structure of the lake, and increasing its stratification and resistance remixing. Both of these may be associated with significant effects on the lake's ecosystem, as follows:

- Reduced mixing may prolong the periods of reduced lake clarity (see *Lake Tahoe Clarity* graph on the following page) that have been observed to occur following years of heavy stream runoff. Mixing disperses fine sediment throughout the volume of the lake, resulting in increased clarity. Decreased mixing helps retain small particles in the top thermal layer of the lake (the epilimnion), where they have maximum impact on lake clarity. Fine particles scatter light and limit how far into the lake we can see and the decreasing transparency in the lake may, in turn, decrease the depth of the layer in which solar radiation input is concentrated and thus further increase thermal stratification. The rate of decline in the lake's clarity has slowed somewhat over the last decade, but is still of concern.

- Recent evidence shows that global climate change has increased air and lake temperatures in the Tahoe basin. Scientists are concerned that rising air and lake temperatures could increase runoff and the potential for algal blooms.

- The feeding behavior and population structure of zooplankton may be affected by the increased stability of the lake. The increased stability favors smaller and more buoyant species of phytoplankton, changing phytoplankton species composition. Researchers have found that the warming of the lake has not changed the overall biovolume, but rather the relative populations of various diatom species. There are greater numbers of small-sized diatom species in recent years than there were 20 years ago because of reduced mixing in the lake. With less mixing, it is difficult for larger algae to stay suspended at the surface of the lake and allows the smaller diatoms which sink more slowly to proliferate (Winder, Reuter, Schladow, 2008).

- Increased stability may modify the biogeochemical cycling of nitrogen and phosphorus in the lake, reducing the regeneration of nutrients from deep water during years without deep mixing, and enhancing it during the increasingly infrequent years of full mixing. The availability of these nutrients may affect the primary productivity of the lake.

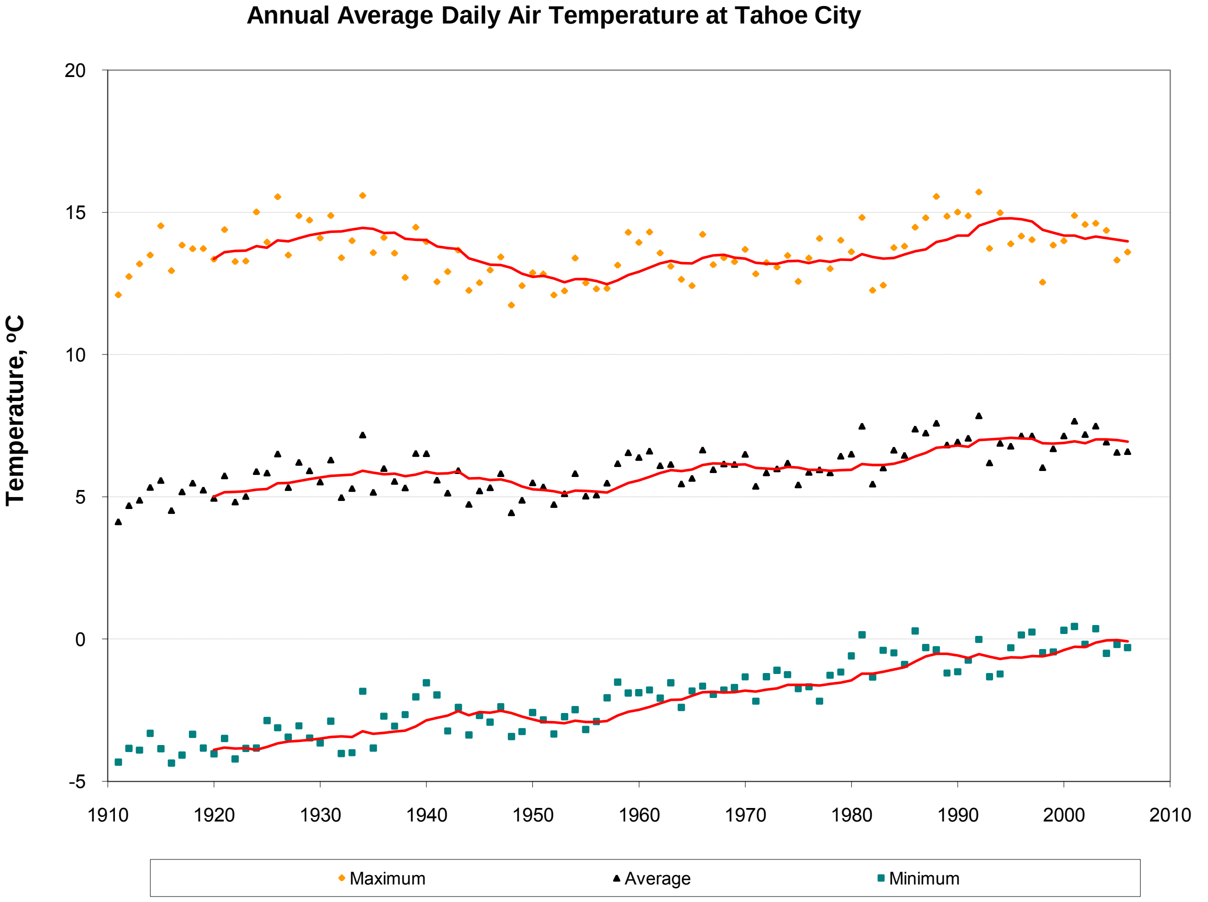


Source: UC Davis TERC

Lake Tahoe is the largest entire lake in North America for which a warming trend has been documented. It joins a growing list of lakes around the globe for which a long-term warming trend has been shown and related to climate change. Trends in the temperature of lakes with deep waters can provide a good indicator of climate change, as short-term changes in surface and near-surface temperature – largely influenced by daily and seasonal temperature – are filtered out in the deep water. (The indicator reflects the temperature of Lake Tahoe waters averaged over the entire volume of the lake.) In Lake Tahoe, the lack of annual deep mixing allows the storage of heat slowly transported downward over a period of years, with partial "resetting" of the deep water to cooler temperatures when deep mixing does occur (Coats, 2006).

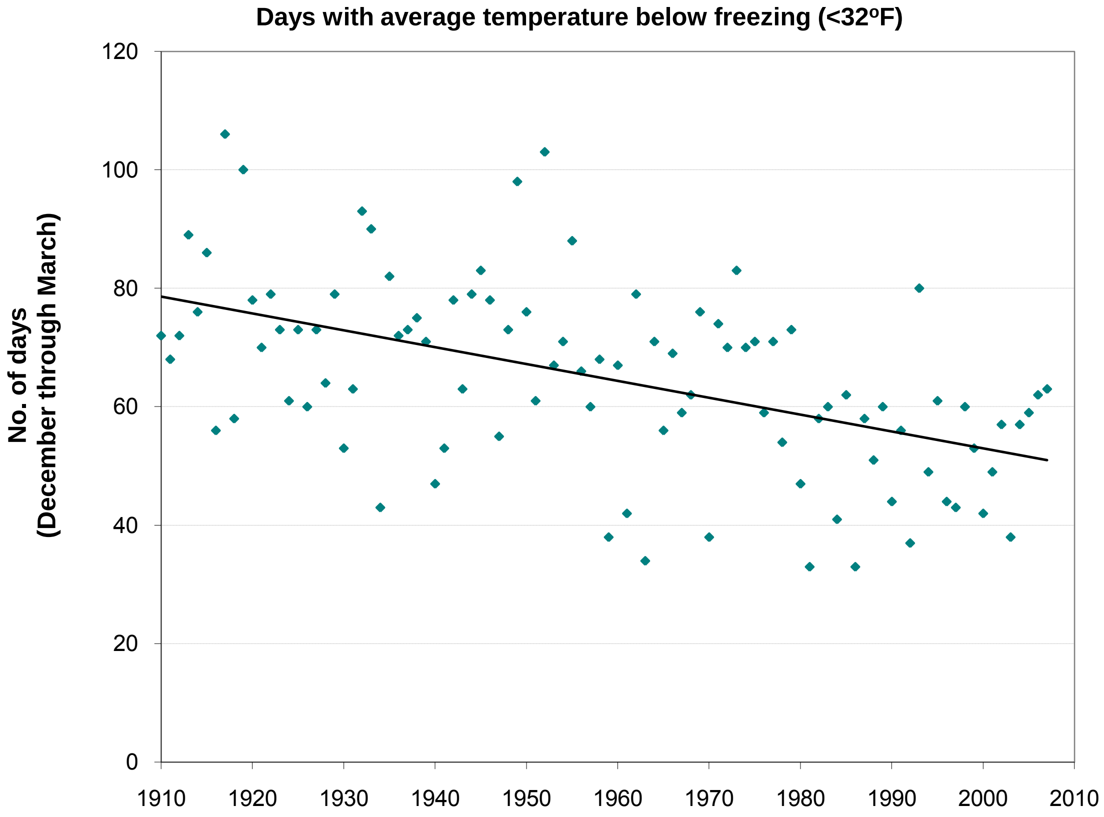
What factors influence this indicator?

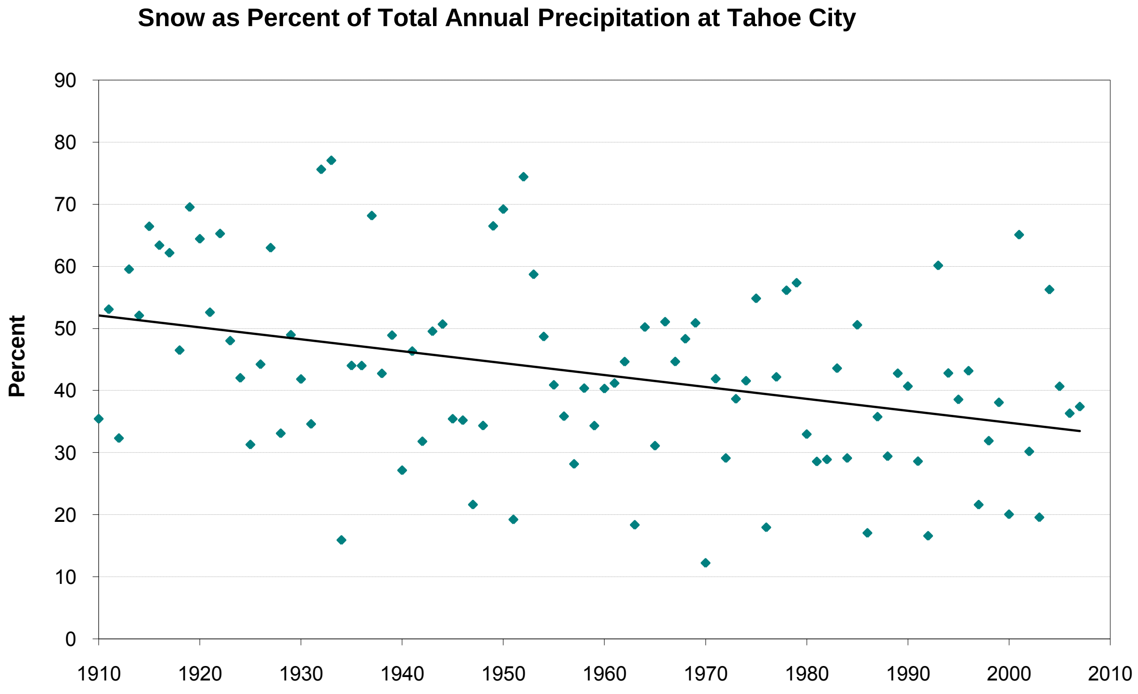
The increasing temperature of Lake Tahoe is related to trends in climate, particularly daily air temperatures in the area. The following graph shows the almost century-long record of daily air temperature in Tahoe City. Minimum daily temperatures have shown a greater increase than either maximum or average daily temperatures.



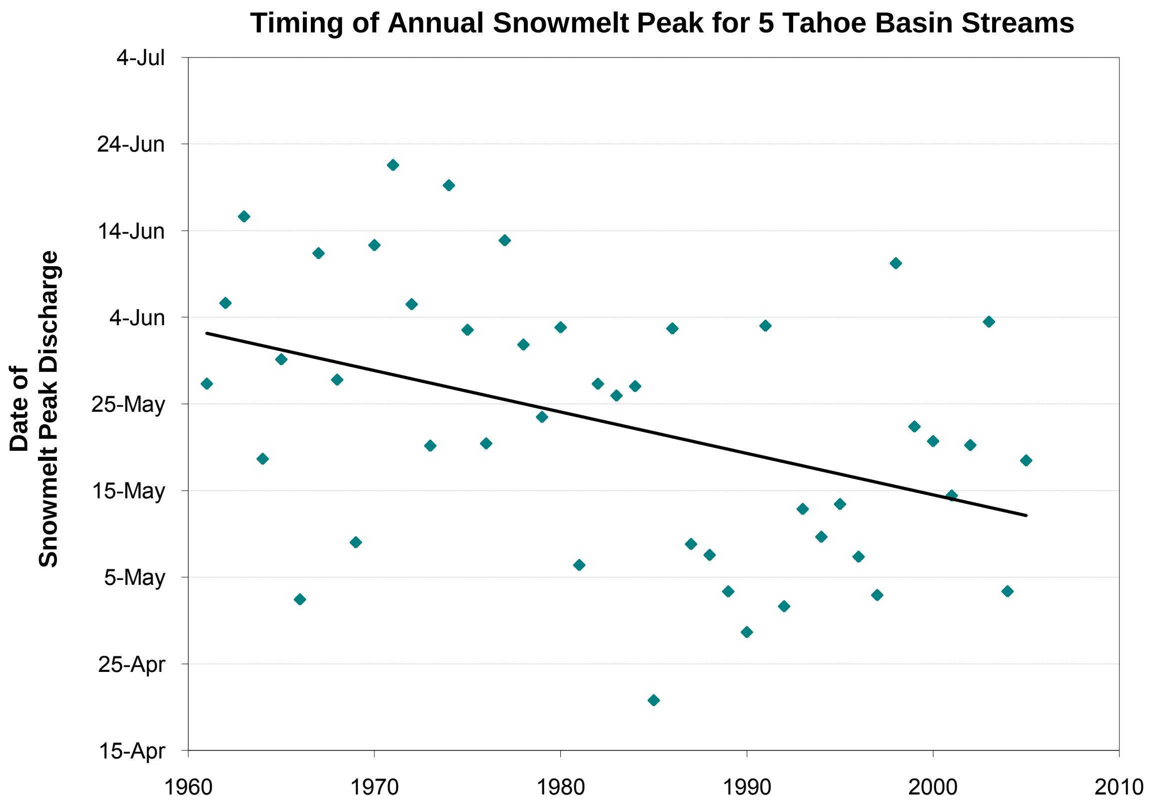
Source: Coats, UC Davis TERC;
(based on climatic data from Easterling, HCN)

The upward trend in winter temperature in the Sierra Nevada has been shown to be related to a trend toward earlier spring runoff (Dettinger and Cayan, 1995). The graphs that follow demonstrate the warming trend in winter temperatures in the Tahoe Basin, and the shift toward earlier peak spring runoff in Tahoe streams. The date of the snowmelt runoff peak (adjusted to remove the effect of total annual snowfall) has shifted toward earlier dates at an average rate of about 0.4 day/year.





Source: Coats, UC Davis TERC;
(based on climatic data from Williams, HCN)



Source: Coats, UC Davis TERC
(based on USGS streamflow data)

Technical Considerations:

Data Characteristics

Lake temperature measurements have been recorded at two locations in Lake Tahoe since 1969: (1) at the Index Station, about 0.3 km off the California side west shore; measurements at depth increments of 2 to 15 m from the surface to a depth of about 100 m have been taken approximately weekly since 1969, and at 1 m increments to a depth of 125 m biweekly since 1996; (2) at the Midlake Station, the exact location of which has varied slightly over time; measurements at nominal depths of 0, 50, 100, 200, 300 and 400 m have been taken at least monthly since late 1969.

Meteorological data are from the Historical Climatology Network (Williams, 2007), and have been corrected for station moves, urbanization effects and other factors. Snowmelt runoff data are for five Tahoe basin streams: Ward, Blackwood, Trout and Third Creeks, and the Upper Truckee River); the effect of total annual snowfall has been removed, and the average residuals converted to date and plotted.

Strengths and Limitations of the Data

It is difficult to use data from a small number of years (2001 to 2007) to draw conclusions about the trend from a slowdown in clarity decline to an improvement in clarity.

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For more information, contact:

S. Geoffrey Schladow
Professor of Water Resources and Environmental Engineering
Director, Tahoe Environmental Research Center
University of California Davis
Department of Civil & Environmental Engineering
(530) 752-3942 (Office)
http://edl.engr.ucdavis.edu

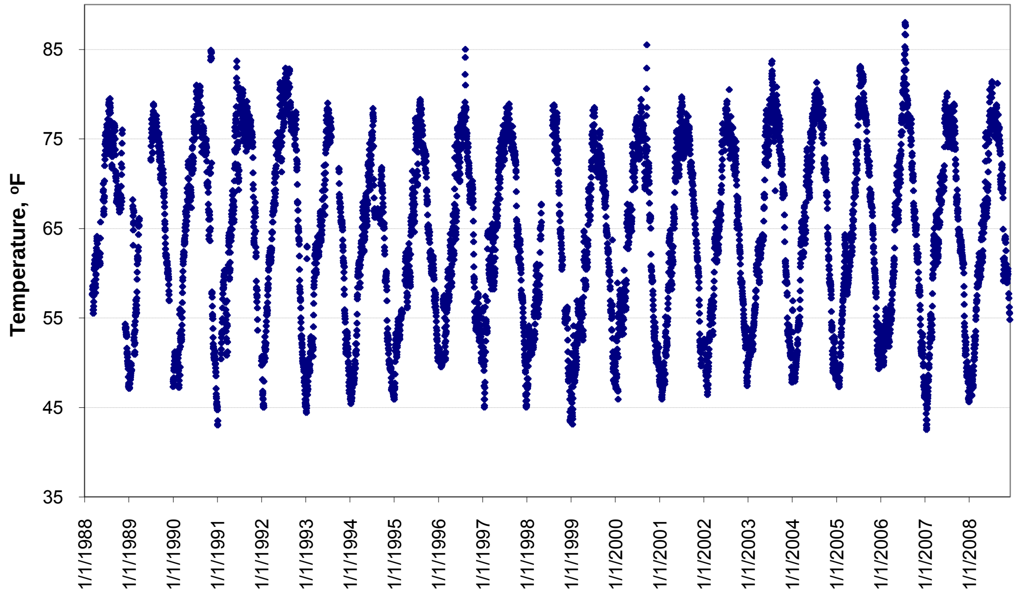
Robert Coats, U.C. Davis Tahoe Environmental Research Center
Coats@hydroikos.com
Patty Arneson, U.C. Davis Tahoe Environmental Research Center
Tahoe Environmental Research Center
Tahoe: (775) 881-7560
Davis: (530) 754-8372
http://terc.ucdavis.edu

Impacts on physical systems

DELTA WATER TEMPERATURE

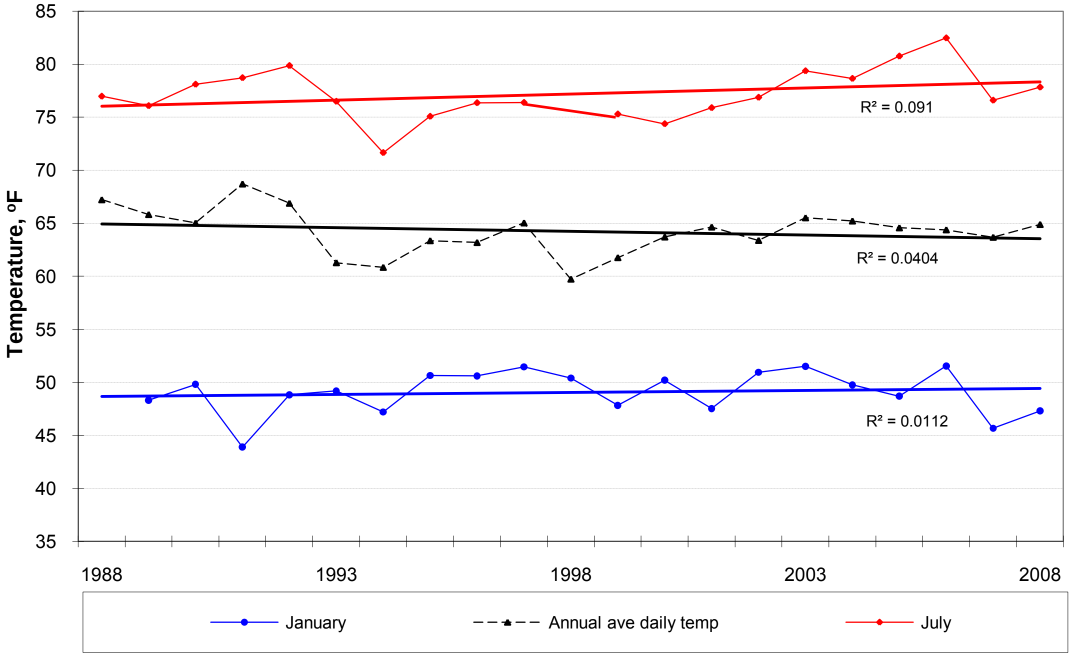
Water temperatures in Clifton Court in the Delta have stayed roughly the same during the past decade.

Daily Water Temperatures
(measured at the Clifton Court Station)



Source: DWR, 2008

Average Water Temperatures: Annual, January and July
(measured at the Clifton Court Station)



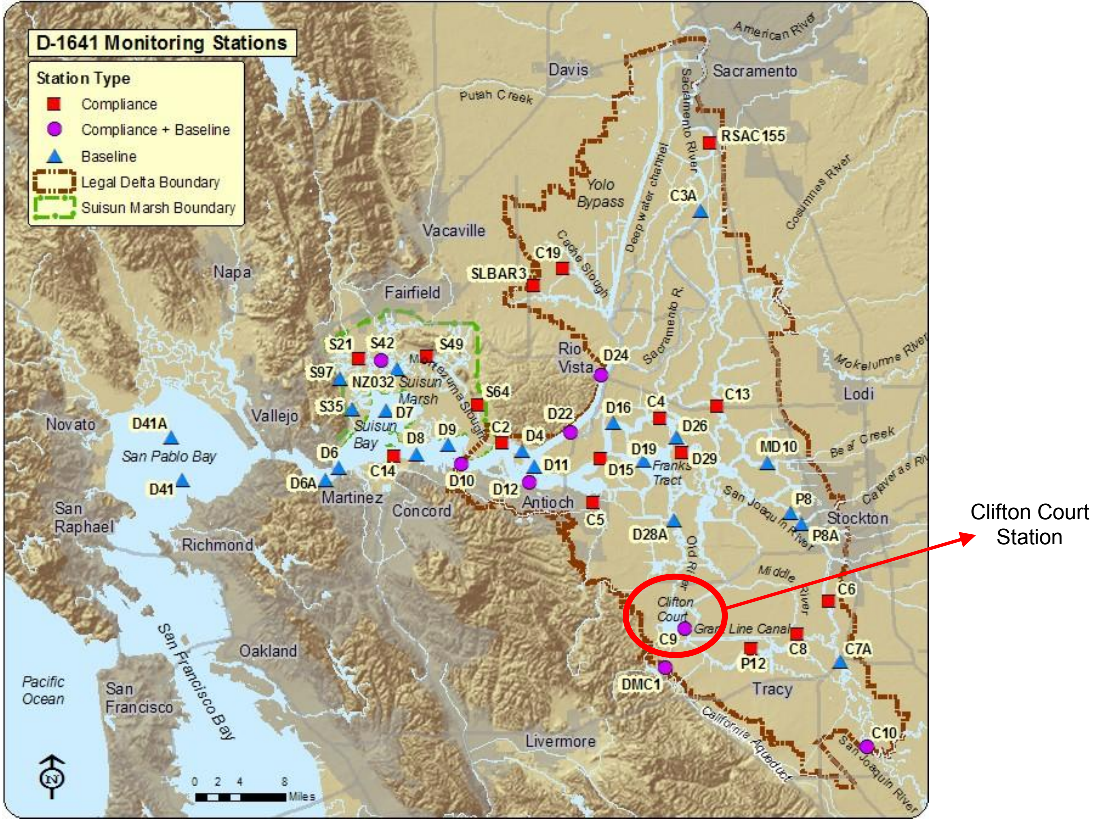
Data Source: DWR, 2008

What is the indicator showing?

No single location can serve as being representative of water temperatures all over the state. For the purposes of this report, water temperatures at the Clifton Court water monitoring station in the southern Delta of the Sacramento-San Joaquin Rivers (see map below) is used as a broad indicator of water temperatures at the heart of the Delta, Central Valley, and of the State's large-scale water-management systems. Clifton Court is the confluence where water from the Sacramento and San Joaquin Rivers join before being pumped into the large-scale State Water and Central Valley Projects for delivery to agricultural and urban users in the southern half of the State.

The top graph presents daily water temperatures. The bottom graph presents the annual average water temperature, plus the averages for January and July, the months with the lowest and warmest water temperatures, respectively.

Location of Clifton Court Monitoring Station



Source: Environmental Monitoring Program, 2008

Clifton Court water temperatures have exhibited a great deal of seasonal variability over the past two decades. However, less year to year variability is seen in more recent years. The annual temperatures vary by as much as 10ºF during the course of the two decades. Some of the coolest years occurred in the 1990s, and the warmest overall years occurred in the early 2000s. Temperatures in the period from summer 2006 to winter 2007 are remarkable for including the warmest temperatures (about 88ºF) and the coolest temperatures (about 43ºF) recorded.

No net trend is evident in the indicator series over the past two decades. Instead the temperatures appear to have fluctuated on roughly decadal time scales, reflecting long term shifts in precipitation, runoff, and air temperatures. Temperatures were warm during the drought period of the early 1990s, cooler during the relatively wet mid-1990s into the early 2000s, and again somewhat warm during the past several years.

Why is this indicator important?

Water temperature is an important factor in the life histories and survival of many aquatic species, from phytoplankton (algae) to fish. When the water grows too warm, phytoplankton can multiply so rapidly that blooms occur (Cloern et al., 2007; Smetacek and Cloern, 2008). Increased water temperatures can adversely impact fish reproduction, growth, development, and even survival (Nobriga et al., 2008; Yates et al., 2008). Warmer (or cooler) waters can encourage encroachment into aquatic habitats by invasive species by making the habitats more suitable for them, or by putting native species at disadvantage (Nichols et al., 1990; Cohen and Carlton, 1995).

Consequently, the future of water temperatures in the State's freshwater habitats will be important to the State's aquatic ecosystems and fisheries. Water temperatures typically depend on the temperatures of the reservoirs and watersheds that supply the water, on how much water is flowing through the channels near the observation point (stagnant waters have more chance to warm in the sun), on upstream management (or lack thereof) of those water supplies, and often locally on air temperatures over the habitat in question (e.g., DWR, 2005). As air temperatures in the State are projected to increase in future decades, many of the State's aquatic habitats will be expected to warm as well. If Delta water flows decline in the future due to either climatic influences or upstream diversions, water temperatures are also likely to increase overall.

Clifton Court is, at least periodically, home to the endangered delta smelt and is near the migration routes of various salmon and steelhead species that make their way through the Delta to upland spawning streams. Thus water at Clifton Court reflects more or less distantly all of the hydroclimatic processes and upstream water and ecosystem management actions in the Sierra Nevada, Coastal Ranges and Central Valley, and may in a sense be a reasonable (if limited) bellwether for net overall changes in water temperatures in a large part of the State. Temperatures at Clifton Court are determined by a combination of climatic and hydrologic influences, and management of streamflows downstream from major reservoirs specifically intended to prevent high water temperatures during key seasons of the year. Monitoring temperatures at Clifton Court would help to determine the extent to which upstream management is preventing climate-change-driven trends towards warmer waters in decades to come.

What factors influence this indicator?

As indicated above, water temperatures at Clifton Court reflect air temperatures in watersheds where the water first runs off, air temperatures in the Delta, flow rates through the Delta, and managed flow releases from cool-water reservoirs. In the future, all of these factors may be expected to change seasonally, from year to year, and on longer time scales. If reservoir and water-resource management are able to undo the effects of long-term warming temperatures associated with climate change on downstream water temperatures (as intended), then the changes at Clifton Court may be more episodic and less trending. Managing water contingencies may appear as short term climatic fluctuations. If climate change proves an overwhelming influence, the water temperatures are likely to warm, more or less along with large-scale air temperatures over the central and northern parts of the State.

Technical Considerations:

Data Characteristics

Water temperatures are measured continually at the Clifton Court station by the California Department of Water Resources, Operations and Maintenance Division, along with conductivity, pH, turbidity, and flow. Hourly measured values are relayed to the California Data Exchange Center (CDEC) and 24 hours' worth of data are averaged each day to obtain the daily averages shown here. Temperatures from the station have been collected and stored in the CDEC for the past decade.

Strengths and Limitations of the Data

Water temperatures are a relatively easy and accurate measurement. The measurement methods have been available and largely unchanging for the past several decades so that values early in this record can be confidently compared to the most recent data.

A key limitation of the data is that the temperatures represent "point measurements", that is, they are temperatures at a certain location and depth in Clifton Court. They are not averages of the entire volume of water in the Court, nor averages of all the flow past the station.

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For more information, contact:

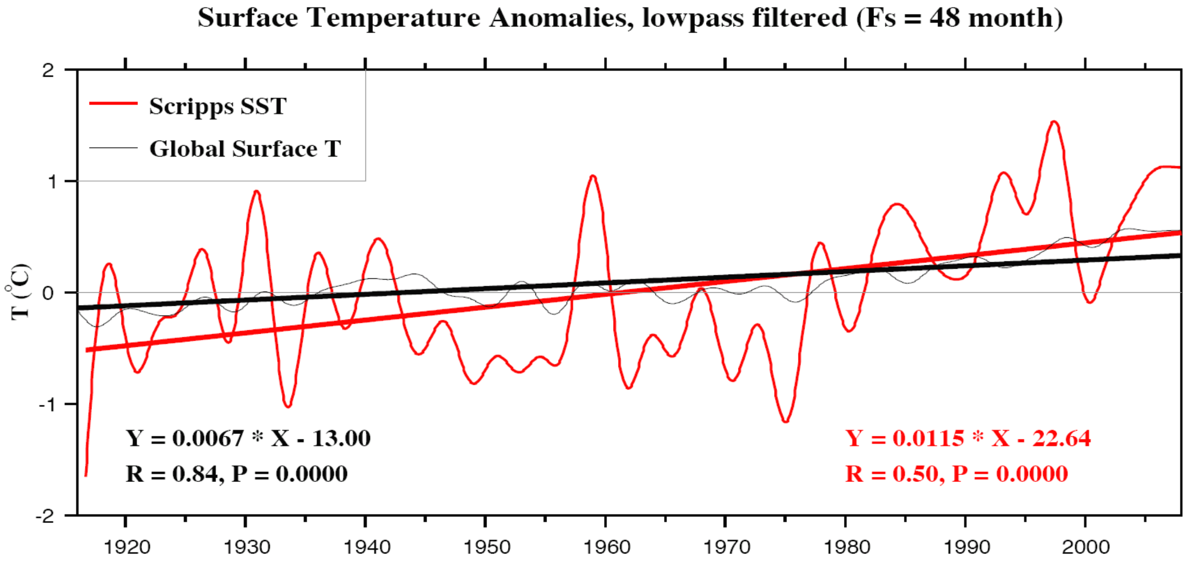
Diane Shimizu
Department of Water Resources
Division of Operations and Maintenance
Environmental Assessment Branch
1416 Ninth Street
P.O. Box 942836
Sacramento, CA 94236-0001
dshimizu@water.ca.gov

Michael Dettinger
California Applications Program
& California Climate Change Center
Scripps Institution of Oceanography
UCSD, Dept 0224
9500 Gilman Drive,
La Jolla, CA 92093-0224
mdettinger@ucsd.edu
(858) 822-1507

Impacts on physical systems

COASTAL OCEAN TEMPERATURE

California ocean temperatures have warmed over the past century.



Surface Temperature Anomalies, lowpass filtered (Fs = 48 month)

Source: Schwing, 2008

What is the indicator showing?

Ocean temperatures along the California coast have risen during the 20th century. Sea surface temperature (SST) measured in La Jolla has increased about 1.1°C since 1916, a rate of approximately 0.0115°C/year. This rate of warming is significantly higher than the global average surface temperature rate of warming (sea and land surface averaged) of 0.0067°C/year (IPCC, 2007).

Why is this indicator important?

Temperature is one of the best-measured, and most reliable, signals of climate change. Global warming is unequivocal; the mean surface has increased by 0.74° C (+/- 0.18) over the last 100 years (IPCC, 2007; NOAA, 2008). The rate of warming has been accelerating; the linear trend over the last 50 years is nearly twice that rate. Coastal ocean warming is consistent with this accelerating trend.

The rate of warming at this location has accelerated over the past 30 years, consistent with the global trend. However the rate of warming locally has been about 70% faster than the global average. Year-to-year variability at Scripps is also much greater than the global mean.

Ocean temperatures contribute to global sea level rise because warming water expands. Warmer waters also play a role in more extreme weather events, by influencing the energy and moisture of the atmosphere. Ecological impacts will include a northward shift in species distributions (Barry et al., 1995). Greater vertical stratification (layers of solar-heated water over layers of denser cold water) of the water column

(Palacios et al., 2004) will reduce upwelling and the movement of nutrients into the photic zone (the depth of the water that is exposed to sufficient sunlight for photosynthesis to occur) reducing biological productivity (Roemmich and McGowan, 1995). Warming in rivers, estuaries, and wetlands could impact reproduction and survival of many species.

Temperature is one of several factors that influence the California marine ecosystem and its populations. It directly affects the range, growth and survival of many species, the location and production of food and predators, and fish catch. SST also represents other factors, including transport and water column structure that affect populations.

Ocean observations (Levitus et al., 2001) and global climate models (IPCC, 2007) confirm that while some of the past variability in surface temperature was due to natural climate fluctuations, global greenhouse gas increases have contributed a significant portion of the observed warming trend. This growing database is an important resource for separating natural from anthropogenic climate changes in our coastal zone. This provides an indication of how future climate change will shape ecosystem structure and productivity, as well as the system's resilience and adaptability to future change.

What factors influence this indicator?

Upper ocean temperatures off California increased by over 1°C during the 20th Century and are projected to rise by another 2-3°C by 2100 (Snyder et al., 2003). Globally, ocean temperatures warm primarily because of the net heat flux from the atmosphere as "greenhouse effect" increases atmospheric temperatures. The world's oceans have warmed to depths of 3000 meters during the past several decades (Levitus et al., 2001). Heat exchange with the atmosphere, which is evidenced by a more rapid rate of warming of near-surface waters, is the source of this trend.

Ocean currents redistribute heat, resulting in a greater warming rate at higher latitudes. Regionally, ocean temperatures can show much different trends, even local cooling (Mendelssohn and Schwing, 2002). On paleo-time scales, oceans have undergone extremes in warming and cooling coinciding with glacial cycles and the varying concentration of atmospheric CO_2 and other greenhouse gases.

The Scripps SST time series is significantly correlated with SST records throughout the north Pacific (McGowan et al., 1998). This means the Scripps SST time series is correlated with time series throughout most of the Pacific, so the interannual variability as well as long-term trend at Scripps is seen throughout the test of the ocean. It also reflects the trend in California upper ocean temperature over the past several decades (Mendelssohn and Schwing, 2002). SST variability relates to fluctuations in many California coastal marine populations as well (Goericke, 2007).

Technical Considerations:

Data Characteristics

Daily SST is measured from the end of the Scripps Institution of Oceanography Pier in La Jolla CA. The proximity of Scripps Pier to the deep waters at the head of La Jolla submarine canyon results in data quite representative of oceanic conditions along the California coast, and throughout much of the California Current marine ecosystem (Roemmich, 1992).

Temperature readings are collected in a Shore Stations Program which provides access to current and historical data records of SST and salinity observed along the west coast of the United States (http://shorestation.ucsd.edu/). Long-term records of ocean temperature are uncommon; the SST time series maintained at Scripps Institution of Oceanography, in La Jolla, extends back to 1916, making this the longest continuous record of its kind on the United States west coast and the Pacific Rim.

For this indicator, the daily temperatures were averaged by month and smoothed by computer with a 48-month low pass filter. A linear trend was computed for each series. The global-averaged surface (sea and land surface temperatures combined), from the NOAA National Climate Data Center (NOAA, 2006), based on Smith and Reynolds (2005), was processed likewise for comparison.

Strengths and Limitations of the Data

Like many climate records, Scripps SST displays considerable interannual variability. El Niño-Southern Oscillation (ENSO) is responsible for anomalously warm (cool) ocean temperatures during El Niño (La Niña) events, with major El Niño events occurring every 5-10 years (UCAR, 1994). The west coast also is affected by multi-decadal variability in temperature, characterized by patterns such as the Pacific Decadal Oscillation, or PDO (Mantua et al., 1997), and the North Pacific Gyre Oscillation, or NPGO. Natural fluctuations in temperature and other physical factors that characterize ocean conditions and affect the marine ecosystem, make it difficult to isolate the magnitude of anthropogenic climate change. However, they also provide an indication of the ecosystem's sensitivity to extremes in temperature and other factors.

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For more information, contact:

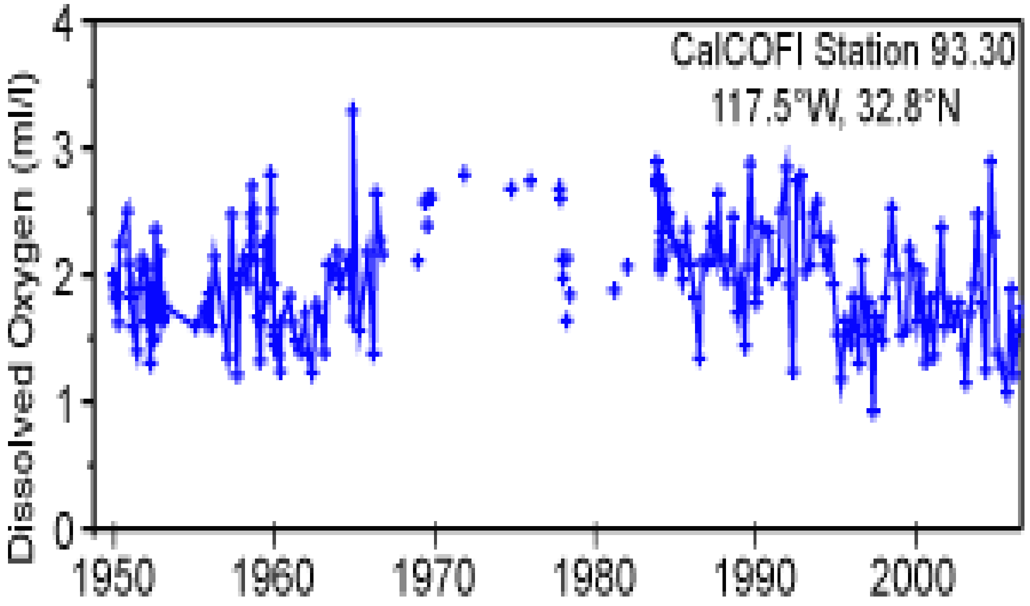
Franklin B. Schwing
Southwest Fisheries Science Center/Environmental Research Division
NOAA Fisheries Service
1352 Lighthouse Avenue
Pacific Grove, CA 93950-2097
(831) 648-8515
Franklin.schwing@noaa.gov

Impacts on physical systems

OXYGEN CONCENTRATIONS IN THE CALIFORNIA CURRENT

Dissolved oxygen levels in the southern California Current System are declining.

Dissolved oxygen levels off the coast of San Diego (at 200 m depth)

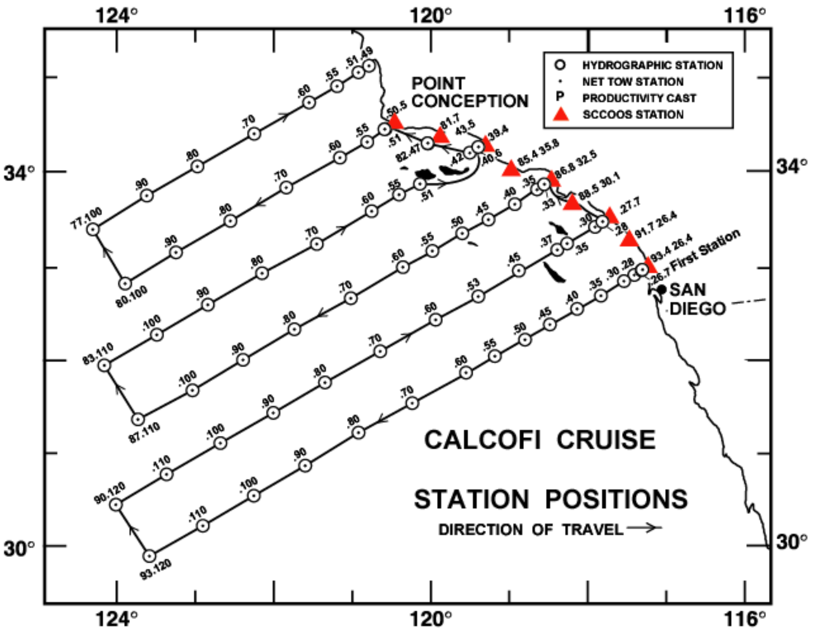


Source: Bograd et al., 2008

Note: The unconnected points denote a period of limited sampling during 1968 to 1983; the connected points denote regular scheduled surveys.

What is the indicator showing?

Measurements of dissolved oxygen concentrations in ocean waters off southern California have revealed a strong and persistent decline since the mid-1980s. As a result, the oxygen-deficient zone (waters having low dissolved oxygen concentrations at depths of about 100 – 1,000 meters) in this area has expanded closer to the surface. The graph above presents levels of dissolved oxygen at a location off the coast of San Diego, in the Southern California Bight (Station 93.30 on the map, next page). At this station, the depth of the oxygen-deficient zone is 90 meters shallower (i.e., moving into the oxygen-rich surface waters) in 2006 than in 1984. This station reveals the significant influence of the California Undercurrent, which transports waters of tropical origin into the Bight. (The Southern California Bight is the 400 miles of recessed coastline from Point Conception in Santa Barbara County, California, to Cabo Colnett, just south of Ensenada, Mexico (SCCWRP, 2008)).



Source: CalCOFI, 2008

Why is this indicator important?

Dissolved oxygen (DO) concentrations in the ocean provide an indication of physical and biological processes occurring in the marine environment, and their impacts on marine ecosystems. Climate change models predict a decline in mid-level concentrations of DO under global warming scenarios. Data from the southern California sampling program that provides the basis for the graph presented (see *Technical Considerations*, below) show large declines in DO between 1984 and 2006. The decrease in DO over the 23-year period was generally less than 10 percent at 50 to 100 meters deep, but ranged from 10 to 30 percent at 200 to 300 meters. These declines are consistent with observations from several regions of the western and eastern subarctic North Pacific. It should be noted that the DO concentrations in the Bight in recent years are similar to those seen in the late 1950s (McClatchie et al., In review).

Declining DO levels in ocean waters, and the associated changes in the depth and extent of oxygen-deficient zones, can lead to significant and complex ecological changes in marine ecosystems. In addition to the direct adverse effects of lower oxygen concentrations (hypoxia), shallower oxygen-deficient zones can also lead to a compression of favorable habitat for certain marine species and an expansion of favorable habitat for other species. During the last decade, the Humboldt squid (*Dosidicus gigas*) – which thrives in low-oxygen environments -- has expanded its range northward from Baja California to southeast Alaska, a shift that may have been affected by changes in the extent of oxygen-deficient zones (Gilly and Markaida, 2007).

What factors influence this indicator?

Oxygen enters the ocean through contact with the overlying atmosphere. It is produced in the oceanic surface layer by biological production, and is removed in sub-surface waters through the decomposition of sinking organic matter. Sub-surface oxygen concentrations are sensitive to the rate of surface-to-deep ocean circulation and mixing and biological production, as well as temperature and salinity (Joos et al., 2003). Hence, concentrations of DO are dependent on a number of physical and biological processes, including circulation, mixing, and biological production and respiration. Climate-driven changes in these processes are likely to be reflected in DO observations.

The declines in DO predicted by climate models are mostly attributed to enhanced thermal stratification near the surface due to warming, and a resultant reduction in the downward transport of oxygen from well-oxygenated surface waters into the ocean interior (Keeling and Garcia, 2002). Significant surface-intensified warming has been observed in the southern California Current System, with a subsequent increase in thermal stratification and large declines in DO levels. Although it has only been documented in the Bight, it is suspected that it has occurred throughout the California Current. These changes are consistent with a hypothesized reduction in vertical oxygen transport.

In addition, the Southern California Bight is impacted seasonally by the California Undercurrent, making it an important location to monitor changes in source waters (i.e., water masses carried into the area by ocean currents) to the southern California Current. The declining oxygen concentrations seen in this region imply a change in the properties of the source waters, although the precise mechanisms of the decline are not known. The declines observed off California are consistent with an observed expansion of the oxygen deficient zone in the tropical oceans (Stramma et al., 2008).

It should be noted that the observed DO levels could be influenced by both local thermodynamic or biological processes, as well as remote, large-scale, changes. The oxygen concentrations can vary with the depth, temperature and time of year of the water being measured. While both factors are important, quantification of their relative influences is not feasible at this time.

Technical Considerations:

Data Characteristics

The data presented are from sampling and monitoring conducted by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program. CalCOFI is a partnership of the California Department of Fish and Game, the National Oceanic and Atmospheric Administration (NOAA) Fisheries Service, and the Scripps Institution of Oceanography. Since 1949, CalCOFI has organized cruises to measure the physical and chemical properties of the California Current System and census populations of organisms from phytoplankton to bird fauna. This is the foremost observational oceanography program in the United States.

Currently, two to three week scientific cruises are conducted quarterly at a grid of ~66 stations off Southern California. At each station a suite of physical and chemical measurements are made to characterize the environment and map the distribution and abundance of phytoplankton, zooplankton and fish eggs and larvae (CalCOFI, 2008). The data reported here are DO concentrations in standard units of milliliters per liter, or mL/L. Details of the CalCOFI sampling protocol can be found at the CalCOFI website, www.calcofi.org.

Strengths and Limitations of the Data

The long historical time series of DO observations from the CalCOFI program provide a unique opportunity to investigate the relative role of physical and biological processes in controlling oxygen changes.

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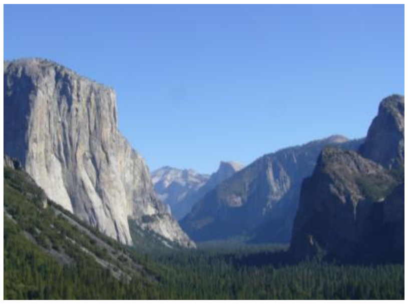
For more information, contact:

Steven Bograd
NOAA/NMFS
Southwest Fisheries Science Center
Environmental Research Division
1352 Lighthouse Avenue
Pacific Grove, CA 93950-2097
(831) 648-8314
steven.bograd@noaa.gov



IMPACTS OF CLIMATE CHANGE ON BIOLOGICAL SYSTEMS

Globally, the scientific evidence suggests that terrestrial, marine and freshwater biological systems are being strongly influenced by recent warming. Studies of regional climate effects on terrestrial species demonstrate responses consistent with warming trends, including poleward and elevational shifts in range; changes in the timing of growth stages (known as "phenology") among species in the Northern Hemisphere, notably the earlier onset of spring events, migration and lengthening of the growing season; and changes in abundance of certain species and community composition. Likewise, studies of marine and freshwater species show observed changes in phenology and distribution associated with rising water temperatures. Finally, there have been a few studies of observed health effects related to recent warming, such as studies associating excess mortality in Europe with high temperature extremes, emerging evidence of changes in the distribution of some human disease vectors in Europe and Africa, and earlier onset and increases in seasonal production of allergenic pollen in certain part of the Northern Hemisphere. However, attributing these impacts to regional changes in climate is difficult due to the influence of non-climatic factors and the intervening effects of adaptive measures taken. (IPCC, 2007)

INDICATORS: IMPACTS OF CLIMATE CHANGE ON BIOLOGICAL SYSTEMS*

HUMANS
Mosquito-borne diseases *(Type II)*
Heat-related mortality and morbidity *(Type III)*

VEGETATION
Tree mortality
Large wildfires
Forest vegetation patterns
Alpine and subalpine plant changes *(Type II)*
Wine grape bloom *(Type II)*

ANIMALS
Migratory bird arrivals
Small mammal migration
Spring flight of Central Valley butterflies
Copepod populations
Cassin's auklet populations

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* Unless otherwise noted, environmental indicators listed are classified as "Type I" (see page 6 for a description of the classification of indicators based on data availability).

Reference:

IPCC, 2007. *Technical Summary. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK. Posted at http://www.ipcc.ch/ipccreports/ar4-wg1.htm

Impacts on biological systems

MOSQUITO-BORNE DISEASES

TYPE II INDICATOR

Mosquito-borne diseases are caused by viruses, bacteria and other pathogens transmitted by mosquito vectors among vertebrate hosts, primarily wild mammals and birds, with humans and domestic animals as incidental hosts. Warmer temperatures are likely to influence the distribution and abundance of mosquitoes and other vectors (such as fleas and ticks), and the incidence of vector-borne diseases. Although there is some evidence that the abundance and distribution of vectors in certain regions of the world may be changing, the evidence for changes in vector-borne diseases is less clear (IPCC, 2007).

California has maintained a comprehensive mosquito surveillance program for over 50 years. Mosquito abundance is monitored using trap counts by mosquito and vector control districts throughout the state. Of the twelve mosquito-borne viruses known to occur in California, only western equine encephalomyelitis (WEE), St. Louis encephalitis (SLE), and West Nile (WN) viruses frequently cause human disease and are carefully monitored by health agencies (DPH, 2008). Because the WEE, WN and SLE viruses are maintained independently in mosquito-wild bird cycles, surveillance of viral transmission within bird populations is also conducted statewide. For human disease surveillance, local mosquito control agencies rely on rapid detection and reporting of confirmed cases to plan emergency control and prevention activities. However, human cases of these mosquito-borne infections are an insensitive surveillance indicator because most persons who become infected develop no symptoms (CDPH, 2008). Thus, despite the long-term monitoring and surveillance data available for California, an indicator presenting the status or trend in mosquito-borne diseases associated with climate change cannot be presented at this time.

Because mosquito and host population interactions are dependent upon ecosystem conditions, changes in climatic conditions may have a profound impact on the transmission of mosquito-borne pathogens. Precipitation amount and pattern determine the quality and quantity of mosquito habitat and food. Temperature impacts the rate of growth of mosquito populations, virus development in the mosquito, its frequency of blood feeding and host contact, and hence the frequency of transmission. One of the potential impacts of long-term warming is the extended geographic range of mosquito populations, the elongation of the transmission season, and the enhanced rate of pathogen transmission.

A recent study (Reisen et al., 2008) analyzed the population dynamics of the mosquito *Culex tarsalis*, a widespread species and important vector of viruses in California. The correlations between *Cx. tarsalis* abundance and ground-based measures of temperature, precipitation and snowpack between 1950 and 2000 in five regions of California were examined. The study reported the following trends as useful in understanding how climate change may impact the transmission of mosquito-borne pathogens and associated human and veterinary health risks:

- The springtime abundance of *Cx. tarsalis* at most trap sites showed a positive correlation with antecedent warm winter temperature (see Figure 1A).

- The *Cx. tarsalis* population response to precipitation varied, with southern California showing strong positive correlations with increasing winter precipitation and the Sacramento Valley showing weak or negative correlations (see Figure 1B).

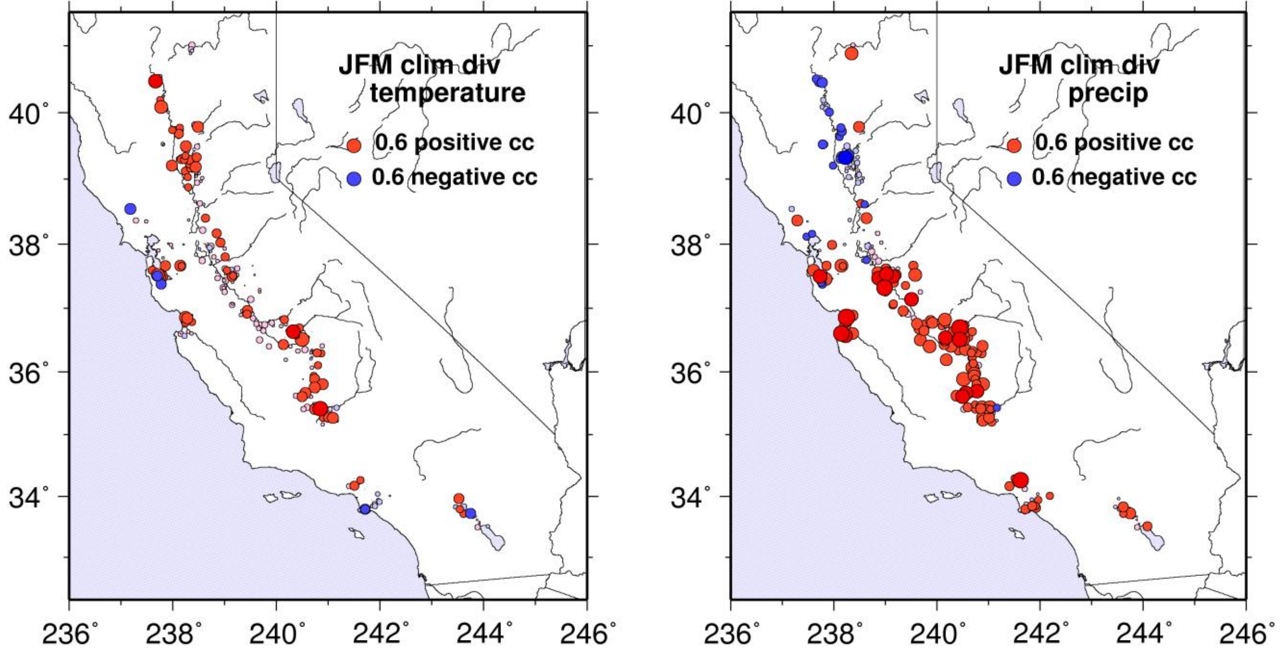

Figure 1A

Figure 1B

Source: Reisen, 2008

Figures 1A and B: Winter [Jan/Feb/March] temperature and precipitation were positively correlated with spring *Culex tarsalis* mosquito abundance. Color and diameter of points show the sign (red = positive; blue = negative) and magnitude of the correlation coefficients [cc]. Data are based on 677 mosquito traps operated from 1950 – 2000.

- Except for the Sacramento region, heavy snowpack was generally associated with increased spring *Cx. tarsalis* abundance.

- The El Niño/Southern Oscillation (ENSO) climatic anomaly associated with cooler and wetter weather in Southern California also showed significant linkages to spring and summer mosquito abundance.

The investigators noted that the findings are generalizations extrapolated from limited data on selected vector-pathogen-host transmission systems. They further state that efforts to link climate conditions to vector-borne disease rarely include sufficient measures of mosquito population size to adequately explore these relationships.

According to the Intergovernmental Panel on Climate Change (IPCC), important non-climate drivers, such as population density, land use and land cover, and public health facilities (e.g., water supply, waste management and vector-control programs) also influence the distribution and incidence of vector-borne human disease. Linking climate-induced changes to mosquito abundance and disease transmission can be better characterized once non-climate determinants have been considered and excluded as significant factors in these complex systems.

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For more information, contact:

UCDAVIS
UNIVERSITY OF CALIFORNIA
William Reisen
Center for Vectorborne Diseases
Old Davis Road
One Shields Avenue
Davis, CA 95616
(530) 752-0124
wkreisen@ucdavis.edu

Impacts on biological systems

HEAT-RELATED MORTALITY AND MORBIDITY

TYPE III INDICATOR

California’s climate is expected to continue to warm during this century. Climate models project average temperatures to rise between 1 and 2.3 degrees Fahrenheit (^{o} F) in the next few decades. In addition to warmer average temperatures, the number of days with extreme heat is also projected to increase -- by 2100, there could be up to 100 additional days per year with temperatures above 90^{o}F in Los Angeles and above 95^{o}F in Sacramento. (California Climate Change Center, 2006). These changes can have direct impacts on human health, including increased heat-related illnesses and deaths.

Heat-related illness is a broad spectrum of disease, from mild heat cramps to severe, life-threatening heat stroke. Children and the elderly, socially isolated populations, outdoor workers, the poor, the chronically ill, and the medically underserved are more vulnerable to the effects of heat than the general population. Many heat-related illnesses and deaths may be preventable, however, if appropriate prevention strategies are adopted and implemented by individuals and communities (DPH, 2008). Heat-illnesses and deaths may also be dependent on the biological adaptability of populations and availability of air conditioning, and thus, are not completely preventable.

Episodes of extreme heat have been associated with increased mortality. Since heat waves are predicted to be more frequent in the future with longer duration and greater frequencies, particularly in urban areas, heat-related mortality is expected to be a greater public health burden (IPCC, 2007). During the July 2006 heat wave in California, at least 140 deaths from extreme heat were recorded by county coroners and medical examiners (Knowlton et al., 2008), although the actual number of total deaths associated with the heat wave is likely to have been more.

While a substantial body of evidence exists that high ambient temperatures can lead to human morbidity and mortality (Basu and Samet, 2002), less is known about the effect of ambient background increases in temperature on human populations. Although studies examining the relationship between mortality and a wide range of temperatures have been conducted on other locales, estimates from these may not be applicable to California, where temperature and humidity are generally mild, and more time is spent outdoors. To help fill this gap, a recent study analyzed California mortality and weather data for nine counties for the warmer months of May to September, 1999 to 2003 (Basu et al., 2008). The study found an increase in mortality from non-accidental causes of approximately 2.3 percent for every 10^{o} F increase in “mean daily apparent temperature” (a measure that reflects both temperature and humidity); risks for persons at least 65 years of age, infants one year of age and under, African-Americans, and those dying from cardiovascular diseases, such as congestive heart failure, acute myocardial infarction and ischemic heart disease, were found to be higher (Basu et al., 2008). This estimate for mortality is independent of air pollutants, and represents exposures to average temperatures, not worst-case exposure scenarios associated with extreme heat. An investigation of the 2006 heat wave (during which mean daily apparent temperatures ranged from 81°F to 100°F in six California counties), the effect was found to be four times higher. In other words, the relationship between mortality and temperature was found to be linear for data during the warmer months of May to September 1999 to 2003; however, during a hypothetical heat wave, the slope of the curve increases at the higher end, based on a preliminary study of the 2006 California heat wave.

The 2006 California heat wave also provided an opportunity to study heat-related morbidity. Dramatic increases across a wide range of morbidities statewide were observed, with over 16,000 excess emergency department visits. The statewide increase in the rate of emergency visits for all causes was found to be statistically significant. The main reasons for the emergency department visits were heat-related illnesses, electrolyte imbalance, acute renal failure, nephritis and nephritic syndrome, diabetes and cardiovascular diseases. By contrast, the increased number of hospitalizations was not significant (over 1,000 excess hospitalizations), although the main causes listed were the same as those for emergency visits, with the exception of diabetes and cardiovascular disease (Knowlton, et al., 2008).

At present, heat-related mortality and morbidity trends are not routinely tracked in the State. Among the sources of data that can be used for analyzing trends are: death certificates, maintained by the Department of Public Health (http://www.cdph.ca.gov/programs/OVR/Pages/default.aspx); records of patient discharge data and emergency department visits by the Office of Statewide Health Planning and Development (http://www.oshpd.ca.gov/HID/DataFlow/index.html); temperature and humidity data from the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climate/research/monitoring.html) and California Climate Tracker (http://www.wrcc.dri.edu/monitor/cal-mon/index.html

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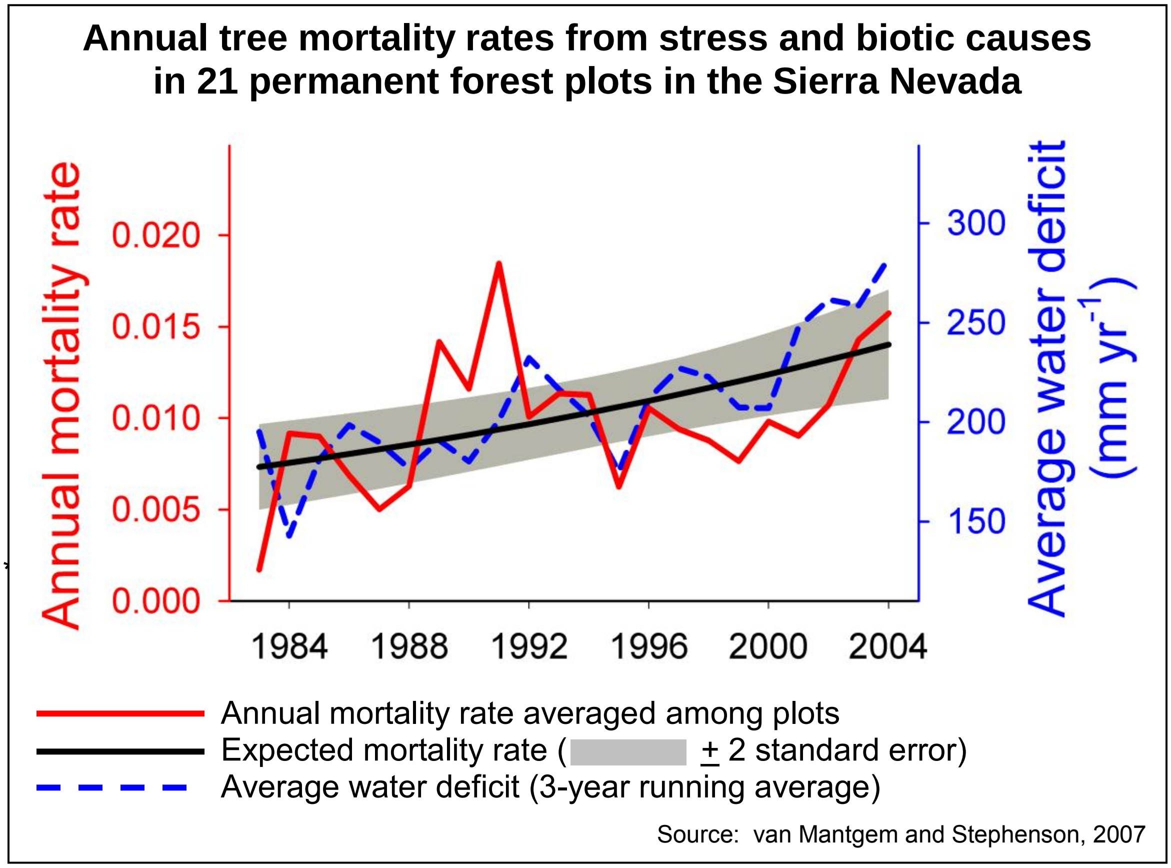
For more information, contact:

Rupa Basu
California Environmental Protection Agency
Office of Environmental Health Hazard Assessment
1515 Clay Street, 16th Floor
Oakland, CA 94612
(510) 622-3156
rbasu@oehha.ca.gov

Impacts on biological systems: Vegetation

TREE MORTALITY

Tree deaths in California's Sierra Nevada increase as temperatures rise.



Annual tree mortality rates from stress and biotic causes in 21 permanent forest plots in the Sierra Nevada

Source: van Mantgem and Stephenson, 2007

What is the indicator showing?

From 1983 to 2004, tree mortality resulting from stress and biotic causes (as opposed to mechanical causes) in temperate old-growth forests of the Sierra Nevada has increased at the average rate of 3 percent per year. The increase in mortality rate coincides with a temperature-driven increase in estimated climatic water deficit, a measure of drought. It is biologically plausible that the water deficit is contributing to increasing mortality rates.

Why is this indicator important?

Tracking the changes occurring in California forests -- particularly in light of the role that forests play in the global carbon cycle — helps improve our understanding of the impacts of environmental factors, including the climate, on the health of forests. Globally, the structure, composition and dynamics of forests appear to be changing, presumably due to rapid environmental changes. For example, the apparent increase in the average global forest net primary productivity may be due to the combined effects of increasing temperature, precipitation, cloudless days, atmospheric carbon dioxide, and nutrient deposition. Global trends, however, are not always echoed by regional trends. Further, forests play a role in the global carbon cycle, and can in turn influence atmospheric concentrations of greenhouse gases.

This indicator is based on a detailed analysis of long-term tree demographic trends in the old-growth coniferous forests of the Sierra Nevada (USGS, 2007; van Mantgem and Stephenson, 2007). Demographic trends reflect mortality and recruitment (recruitment is a measure of how well the trees can reproduce and sustain their numbers). More than 20,000 trees in 21 permanent study plots in Sequoia and Yosemite National Parks were being tracked. Data on annual mortality, including the immediate causes of death over a period of more than two decades were analyzed to determine: (1) changes in mortality and recruitment (growth of new trees) rates in Sierra Nevada forests; (2) whether there are differences among taxonomic groups and forest types (based on elevation); and (3) probable causes of any changes. The analysis showed: (1) tree mortality rate increased -- a change attributable to stress and biotic causes -- while recruitment rate was unchanged; (2) increased mortality rates across taxonomic groups and forest types; and (3) a correlation between mortality rate and water deficit.

Modeling studies suggest that, over a period of decades, even small changes in mortality rates can profoundly change forests. However, few studies of real forests have examined possible environmental drivers of changes. The study on which this indicator is based provides the first detailed analysis of long-term, high-resolution tree demographic trends in old-growth temperate forests. The findings indicate that Sierra Nevada forests appear to be sensitive to temperature-driven drought stress. Hence, continued increases in temperatures without compensating increases in precipitation have the potential to dramatically alter these forests.

Trends in tree mortality may serve as an early warning of acute changes, such as sudden forest die-back. Tracking these trends will help inform management practices in water-limited forests, where increasing temperatures may increase the vulnerability of trees to other stresses, such as competition or tree pathogens. This information also has implications for establishing target reference conditions for forest restoration efforts.

What factors influence this indicator?

Tree death is a complex process that often involves a lengthy chain of events, making it problematic to assign a single ultimate cause of death. The indicator is based on tree mortality information that focused on the immediate, or proximate, causes of death – i.e., the final agent that killed trees. These causes can be categorized into two classes: stress and biotic causes (e.g., insects and pathogens, and direct physiological stresses, such as from competition), or mechanical causes (e.g., breaking or uprooting by wind or snow).

Over the study period, overall mortality rate nearly doubled, increasing at an average rate of 3 percent per year. Mortality attributed to stress and biotic causes also increased at an average of 3 percent annually, a rate higher than that attributed to mechanical causes, which was largely unchanged.

The study analyzed several factors that are potentially driving the long-term changes in demographic rates. These factors include the intensity of competition within stands, ozone pollution, and changes in climate. Neither competition nor ozone concentrations were found to be correlated with mortality. Water deficit, an index of drought which integrates temperature and precipitation, was found to be correlated with the increase in stress and biotic mortality rates. Water deficit can increase with increased evaporative demand, decreased water availability, or both. Based on their analysis, the investigators conclude that the forests may be experiencing increasing deaths related to temperature-driven evaporative stress, potentially making them more vulnerable to extensive die-back during otherwise normal periods of reduced precipitation.

Increased mortality occurred across taxonomic groups. *Abies* (firs) and *Pinus* (pines) are the dominant groups in the study plots, together making up about 75 percent of all trees. *Abies* is considered shade-tolerant and drought-intolerant, while *Pinus* is moderately shade-intolerant and drought-tolerant. The mortality rate for *Abies* and *Pinus* increased at average rates of 10 percent and 3 percent per year, respectively. The effects of an exotic pathogen on certain *Pinus* trees likely contributed to the greater increase in mortality. Additionally, all forest types showed increasing mortality rates, except the subalpine plots at the highest elevations (2900 to 3500 meters).

Finally, the increase in mortality rate has predominantly affected small trees. Large trees can survive moderate droughts as they have more extensive root systems and greater ability to store resources. However, seedlings require prolonged water and the slow release of snowpack late into the spring ensures that they will have sufficient water to carry them into the next winter's water cycle. Snowpack has been diminishing earlier in the spring over the past fifty years leaving the seedlings vulnerable to desiccation in the dry soil.

Technical Considerations:

Data Characteristics

The data represent more than two decades of monitoring trees in 21 permanent study plots established between 1982 and 1996 in old-growth stands, within the coniferous forest zones of Sequoia and Yosemite National Parks. The study plots are arranged along a steep elevational gradient from near lower to near upper treeline, and encompass several different forest types, as follows: low elevation, at 1500 to 1700 meters (m), dominated by ponderosa pine-mixed conifer forest; mid-elevation, at 2000 to 2300 m, dominated by white fir-mixed conifer forest; high elevation, at 2400 to 2600 m, dominated by red fir and Jeffrey pine forest; and very high, at 2900 to 3500 m, dominated by subalpine pine species.

Within the plots, trees that are at least 1.37 m in height were tagged, mapped, measured for diameter, and identified to species. The plots were monitored annually for tree mortality. In addition, each tree was examined annually, and the presence of any damage, pathogens, etc., recorded. At approximately 5-year intervals, the diameter of each living tree was measured. Prior to 1999, the number of trees reaching 1.37 m initially during the years when diameter measurements were recorded to determine recruitment; annual estimates of recruitment were derived by evenly distributing counts of new recruits in the intervening years between diameter measurements. Beginning in 1999, recruitment was measured annually.

Data for the parameters included in the correlational analyses were from the following sources (see secondary references cited in van Mantgem, 2007): *Stand-level indices of competition* were estimated from stand density and above-ground living stem biomass using standard allometric equations tailored to the Sierra Nevada. *Climatic data* were estimated by interpolation from instrumental records and a digital elevation model, using the Parameter-elevation Regression on Independent Slopes Model, or PRISM. An index of *ozone pollution* was derived based on annual average summer (June to September) daily maximum ozone concentration from the longest continually running monitoring station at Sequoia National Park.

Strengths and Limitations of the Data

The study plots have not experienced recent disturbances, such as fire or avalanche, and have never been logged. Certain trees, such as those with missing data and trees that had grown at least 1.37 m tall but died before they can be included in recruitment counts, were removed from analysis. Data for a total of 21,338 trees are included in the analysis.

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For more information, contact:

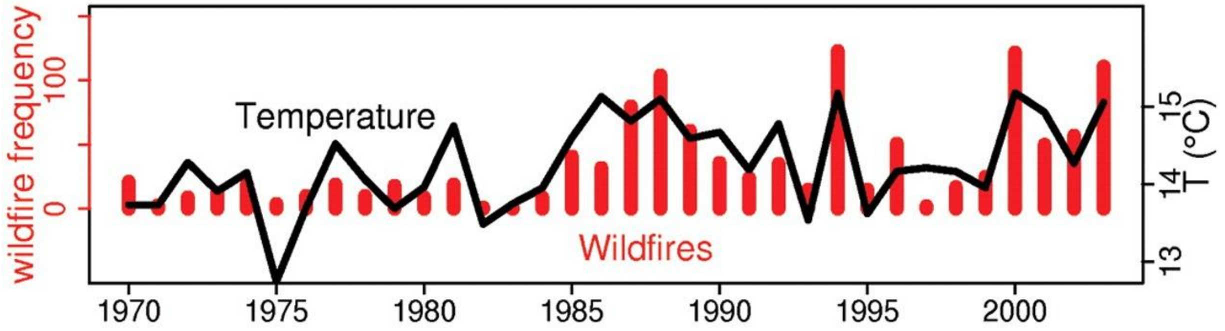
Phil van Mantgem
U.S. Geological Survey, Western Ecological Research Center
Sequoia and Kings Canyon Field Station
47050 Generals Highway
Three Rivers, California 93271-9651
(559) 565-3179
pvanmantgem@usgs.gov

Impacts on biological systems: Vegetation

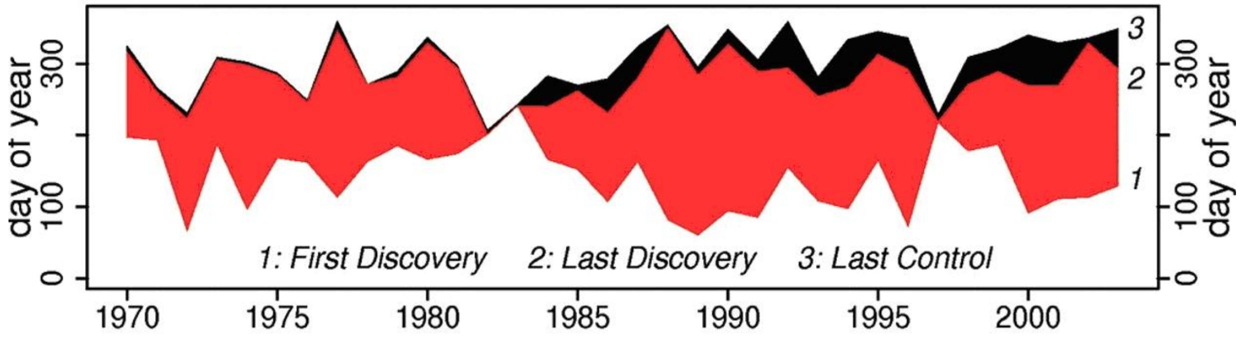
LARGE WILDFIRES

Large-wildfires (1000 acres and greater) and fire season length are increasing in tandem with rising temperatures.

Frequency of large western United States forest wildfires (bars) and mean March through August temperature for the western United States (line)



Time between the reported first large-wildfire discovery and the last large-wildfire control date



Source: Westerling et al., 2006

What is the indicator showing?

Large-wildfire (herein "wildfire" refers to a large-fire event ≥400 hectares (1,000 acres)) activity in western U.S. forests increased suddenly and markedly in the mid-1980s. From 1987 to 2003, wildfire frequency was nearly four times the average number, and the total area burned was more than six times the level seen between 1970 and 1986. Interannual variability in wildfire frequency is strongly associated with regional spring and summer temperature. Also, when comparing 1970-1986 with 1987-2003, the length of the yearly wildfire season (March through August) extended by 78 days, a 64 percent increase, and the duration of individual fires increased from one week to about five weeks.

Why is this indicator important?

Wildfire in the West is strongly seasonal, with 94 percent of fires and 98 percent of area burned occurring between May and October. In many parts of California, the fire season peaks in August and September (Westerling et al., 2003). Large fire behavior has become more erratic with large flame lengths, torching, crowning, rapid runs and blowups due to extremely dry conditions (Brown et al., 2004).

Wildfires have caused concern in recent years due to the severity and expanse of the areas they have consumed, including hundreds of homes burned and devastating damage to natural resources. Modeling of wildfires in California predicts that the largest changes in property damage will occur in wildland/urban interfaces proximate to major metropolitan areas in coastal southern California, in the Bay Area, and in the Sierra foothills northeast of Sacramento. The threat of wildfire in the future will be enhanced as more population moves into the Sierra Nevada foothills (Westerling and Bryant, 2008).

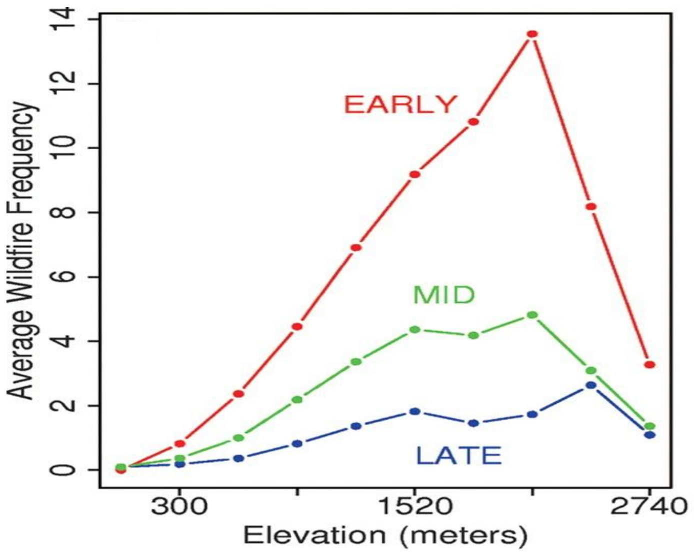
The increased frequency of wildfires in the western U.S. will lead to changes in forest composition and reduced tree densities, thus affecting carbon pools. It is estimated that these forests sequester 20-40 percent of total U.S. carbon. If wildfire trends continue, this biomass burning will result in carbon release, suggesting that western U.S. forests may become a source of increased carbon dioxide rather than a sink (Schimmel and Braswell, 2005).

What factors influence this indicator?

Since 1986, the combination of earlier snowmelt due to warmer springs (resulting in a longer fire season), and warmer summers (resulting in lower soil moisture) have been the major contributors to the increase in fire activity in both managed and unmanaged forests (Westerling et al., 2006) . The hydrology of the western United States is dominated by snow; 75 percent of annual streamflow comes from snowpack. Snowpack keeps fire danger low in these arid western forests until the spring melt period ends. Once snowpack melting is complete, the forests can become combustible within one month because of low humidity and sparse summer rainfall.

The average frequency of western U.S. forest wildfire by elevation and early, mid-, and late snowmelt years from 1970 to 2002 is depicted below. Increased wildfire activity has been concentrating in elevations between 1,680 and 2,590 meters (5,500 to 8,500 feet). Overall, 56 percent of the wildfires and 72 percent of the total area burned occurred in early snowmelt years. By contrast, only 11 percent of the wildfires and 4 percent of the total area burned occurred during late snowmelt years.

Forest Wildfire Frequency and the Timing of Spring Snowmelt*

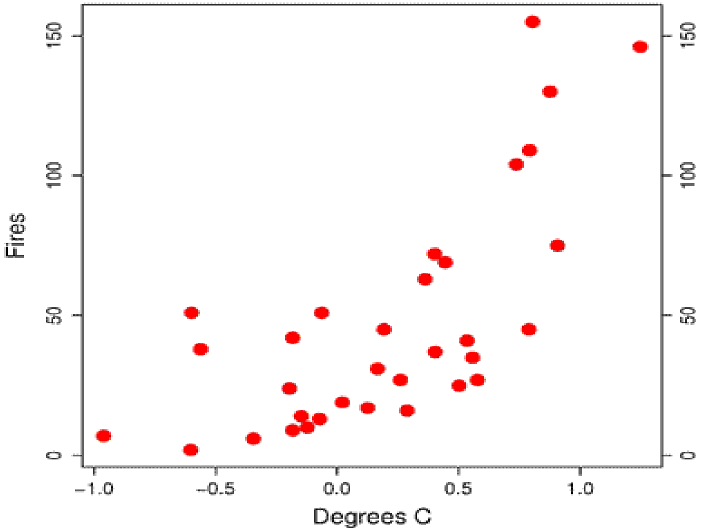


Source: Westerling et al., 2006

** The designations "early," "mid" and "late" correspond to each tercile of dates of the center mass of annual flow for snowmelt-dominated streamflow gauge records in western North America (see cited reference).

Based on comparisons with climatic indices that use daily weather records to estimate land surface dryness, the increase in wildfire activity can be linked to an increase in spring and summer temperatures by ~0.9 degrees C and a one to four week earlier melting of mountain snowpack (Westerling et al., 2006). Above-average spring and summer temperatures in western forests have a dramatic impact on wildfire, with a highly non-linear increase in the number of wildfires above a certain temperature threshold (see graph which follows).

Annual number of large forest wildfires vs.
Average Spring and Summer Temperatures for the Western U.S.



Source: Westerling, 2008

Forests with the highest average moisture availability and biomass have the most fires when conditions are much drier than normal because fuel flammability is the most important factor determining fire risks. Therefore, early springs and dry summers tend to increase the risk of large fires in forests. Higher altitude forests are buffered against climate change warming effects to some extent by available moisture from colder conditions; thus more snowpack and abundant spring runoff. The runoff provides moisture to the soil and vegetation, reducing the flammability of these forests. At lower, warmer elevations, with winter precipitation falling as rain instead of snow, and without the prolonged spring snowmelt, a longer summer dry season increases the forest's vulnerability to wildfires.

In contrast to forests, the number of wildfires in the western United States grass and shrublands is not significantly correlated with average spring and summer temperatures (Westerling, 2007). These types of vegetation tend to occur at lower elevations and latitudes, that either do not receive as much snow, or do not have snow on the ground for as long; hence, the intensity of summer drought has a less pronounced effect. Fuel availability is a limiting factor for wildfire risk in these arid hot environments where accumulated fuels may be insufficient to sustain a large fire in some years. Fires tend to occur in or following relatively wet years because wet winter conditions foster the growth of grasses that quickly cure out in the very hot summer dry season, providing a load of fine fuels that could foster the ignition and spread of large fires (Westerling, 2008).

In some ecosystems fire suppression and land uses (e.g., livestock grazing and timber harvesting) that reduce fire activity in the short run have led to increased fuel loads today. Formerly open woodlands have become dense forests, increasing the risk of large, difficult-to-control fires with ecologically severe impacts in the immediate future. These changes have fueled large, stand-replacing crown fires in Southwestern ponderosa pine forests, where they were rare under natural fire regimes (Allen et al., 2002). In these ecosystems, it is difficult to ascertain the relative contributions of management factors versus climate change.

Changes in population and land use can have immediate and dramatic effects on the number and sources of ignitions and on the availability and flammability of fuels. Over the long term, fire management and land uses that suppress surface fires can lead to changes in the density and structure of the vegetation biomass that fuels wildfires, changing the likelihood of a large or severe fire occurring.

The effect of climate change on precipitation is also a major source of uncertainty for fuel-limited fire regimes. Managed wildfire regimes still contain strong climate signals that are similar to ancient fire regimes based on fire reconstructions from tree rings. Large-scale current patterns in the Pacific Ocean may modulate sea surface temperature anomalies which, in California may promote droughts in La Niña years and during the warm cycle of the Pacific Decadal Oscillation. Conversely, in El Niño years, buildup of fuels occurs as a result of heavy precipitation (Westerling and Swetnam, 2003).

Technical Considerations:

Data Characteristics

A large wildfire here is defined as one affecting over 400 hectares (1000 acres). A comprehensive database of 1166 large wildfires in western United States forests from 1970 (when data became available) to 2003 were compared with hydroclimatic indices that use daily weather records to estimate land surface dryness. The large-fire history for western United States forests was compiled from individual fire records for units of the United States Department of Agriculture's Forest Service and the National Park Service. Researchers compared the times series, the timing of snowmelt and spring and summer temperatures for the same 34 years. For the timing of peak snowmelt in the mountains for each year, the streamflow gauge records from 240 stations throughout western North America were used.

Strengths and Limitations of the Data

Over 90 percent of reported fires are very small, and are not as responsive to climatic influences. The climate signal in the large fires, which are much more relevant in terms of their impact, tends to get lost in all the noise about smaller fires. Less than 5 percent of all wildfires account for more than 95 percent of all the area burned (Westerling et al., 2006).

Documenting increases in large wildfire frequency can be difficult because the incidence of wildfire naturally varies greatly in interannual to decadal timescales, necessitating a long record in order to detect significant trends in wildfire activity. On the other hand, long records that document wildfire activity are often not readily available and older records are less comprehensive than recent records, meaning fires can appear to be increasing merely because of improved reporting. Reconstructions of past wildfires from fire scars preserved in trees and from charcoal records from sedimentary cores, combined with reconstructions of past climate from tree rings, ice cores, and corals, can also give us insights into how wildfire responds to climate variability.

Not all causes of fires are climate-related but hot dry conditions can exacerbate ignitions from lightning, arson, and equipment use. In California, the official fire season is that portion of the year, generally 6 to 8 months in the summer and fall, declared such by the responsible public agency fire administrator. Declaration is based on fuel and weather conditions conducive to the ignition and spread of wildland fires. This differs from the definition of the fire season described in the work above, which is defined as the time between discovery of the first large fire and date the last large fire is declared under control.

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For more information, contact:

THE UNIVERSITY OF CALIFORNIA MERCED

Anthony L. Westerling
Sierra Nevada Research Institute
P.O. Box 2039
Merced, CA 95344
(209) 228-4099
awesterling@ucmerced.edu

Impacts on biological systems: Vegetation

FOREST VEGETATION PATTERNS

Sierra Nevada forests species and land cover have been changing since 1934.

Figure 1

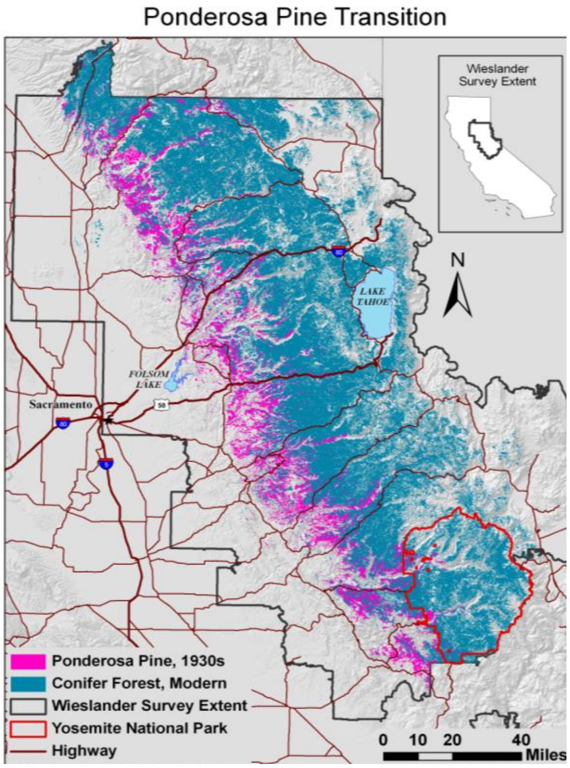
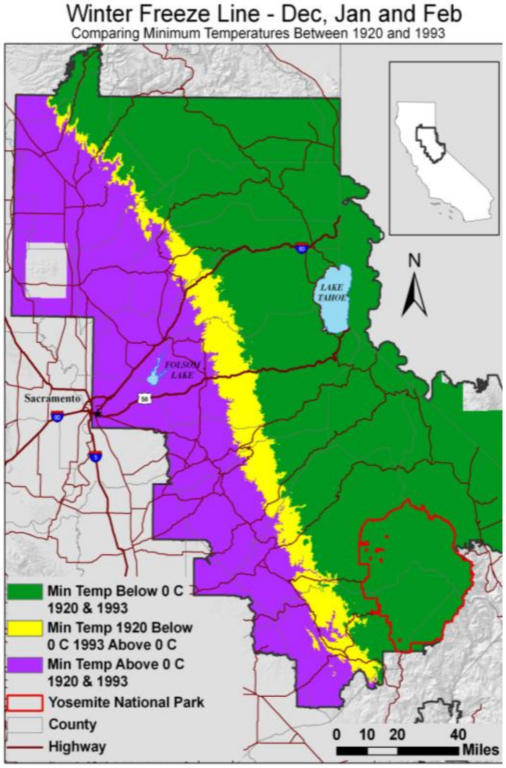


Figure 2



What is the indicator showing?

The lower edge of the conifer-dominated forests of the Sierra Nevada has been retreating upslope over the past 60 years (Figure 1). The dark blue areas are the regions that still are dominated by the Sierran conifer forests, including the well-known forests leading up to the Lake Tahoe Basin. The area in pink was historically occupied by ponderosa pine (*Pinus ponderosa*), the pine that extends the lowest of the group of conifers making up the mixed conifer forests of the Sierra Nevada Mountains. That this lower edge is contracting is consistent with predicted forest response to future climate change (Lenihan et al., 2003) which predicts an expansion of broadleaf-dominated forests in this elevation zone, with the accompanying loss of conifer-dominated forests. Figure 2 shows warming captured by weather stations over the past 100 years. The area in yellow used to be frozen at night between December and February in 1920; since 1993, the average monthly minimum temperature in this area during the same months has been above 0^{o}C. The purple region to the west represents the areas in which monthly average minimum temperatures have exceeded 0^{o}C over the winter since 1920, and the green region to the east is the area that was and still is frozen at night from December through February.

Why is this indicator important?

Since each plant species is adapted to certain environmental conditions, changes in the distribution of dominant plants can potentially be both an indicator of, and a response to climate change. As conditions warm, species are generally expected to move towards the poles, and to higher elevations. At the lower edge of the Sierra Nevada Mountains' conifer forests, there has been a transition to oak-dominated and chaparral vegetation.

The shift in vegetation from needle-leafed to broad-leafed trees and chaparral is a significant change, with consequences for species that inhabit this region. Birds, mammals and other species that rely on acorns and oaks for food and habitat will find more of this type of habitat available, while species that depend on pine nuts and pine trees will find fewer resources. The change to oak-dominated ecosystems means these areas dry out more quickly, and they will also possibly burn more frequently. Moreover, the temperature of the microenvironment will also be different, due to the differing amount of shade and the physical structure of the trees and shrubs making up the majority of the area.

The upslope retreat of conifers is a clear biological signal that conditions are changing. Since the snow pack of the Sierra Nevada is a vitally important resource for the people, plants and animals, and the lower edge of the snowpack is also associated with the conifer belt, the upslope retreat of conifers may be a physical measure we can use to monitor what regions of the Sierra still support a snow pack.

There are several types of change that could potentially be measured from the vegetation maps. As one walks in the alpine areas above the tree line, the discovery of a new set of tree seedlings, recently established, would be evidence that those trees had found some suitable condition and moved upslope, into the area. This phenomenon can be considered a leading edge dynamic – that is, new establishment at the advancing edge of a species' range. At the opposite, retreating end of a species' range, change may be harder to detect, and is driven by mortality, along with the inability of seedlings to survive under unfavorable conditions.

What factors influence this indicator?

The area in which this forest dynamic is occurring is at the same elevations which are experiencing a warming of winter nights. On average, these areas used to be frozen in December, January, and February, but now are not (the yellow area in Figure 2). This upwards migration of the freezeline means that should a storm drop snow in the yellow zone, that snow will no longer stick, and will melt within a few days. In turn, this means that the countdown to summer drought conditions starts from the last precipitation event of the year, since there is no stored water in a snowpack to be released through melting. Therefore, summer drought conditions begin earlier, as also evidenced by the advancing spring snow melt, and it is documented throughout the western United States (Stewart et al., 2005).

This rise in temperature and associated drying is not likely to kill adult ponderosa pine trees directly. This tree species is very robust to heat and drought and a gradual warming may not kill the adult trees. However, if the seedling establishment conditions have changed enough, the sequence of events is likely to proceed as follows: 1) a stand-replacing disturbance occurs on a site; this can be a fire that kills the adult trees (fires are increasing throughout the west (Westerling et al., 2006)), a logging clear cut, or other disturbances such as a bark beetle outbreak or a disease that affects the adult trees 2) subsequent to the adults being killed off, the seeds and seedlings are not able to survive long enough to allow a new stand of trees to establish. Seedlings may be susceptible to a number of causes of mortality: desiccation due to increased aridity; root competition for water by other species, particularly chaparral shrubs and non-native grasses; or increased fire frequency, which kills all the seedlings. Long-term vegetation plot studies corroborate the trend that the map analysis illustrates, by documenting an increase in seedling mortality in Sierra Nevada conifers (van Mantgem and Stephenson, 2007).

Technical Considerations:

Data Characteristics

This indicator is based on a study which compared vegetation maps made in two time periods spanning 60 years: the Wieslander Vegetation Type Survey of the 1930s, and the US Forest Service Calveg map, created in 1996. The climate trend information depends on reconstructions of historical climate from weather stations in the study area. The climate study was originally conducted by Parra and Monahan (2008), who produced monthly summaries of California mean, maximum, and minimum temperatures for every year starting in 1900, using a 1 km^{2}grid size.

The Wieslander Vegetation Type Mapping (VTM) project was a US Forest Service survey that began in the late 1920s and ran into the early 1940s, meant to inventory the forests of California (Wieslander, 1935a; b)(Wieslander 1935a, 1935b). Directed by Albert Wieslander, project surveyors would ascend to ridge lines and draw the patterns of the vegetation they observed on topographic maps, coding the polygons they drew with symbols representing the dominant species in each mapped unit. Maps were drawn for about one third of the state, including most of the Sierra Nevada Mountains, the Coast Ranges from the San Francisco Bay Area to the Mexican border, and scattered quadrangles in the far northwest of the state. They also surveyed over 16,000 vegetation plots, took over 3,000 landscape photographs, and left notes associated with each quadrangle surveyed. Over the past five years a consortium of university groups has been digitizing the work (Kelley et al., 2005). The photographs are available for viewing at: http://www.lib.berkeley.edu/BIOS/vtm/; the vegetation plots are available for download from the UC Berkeley VTM project website: http://vtm.berkeley.edu/. The VTM maps are being digitized (Thorne et al., 2006); currently the Sierra Nevada and Bay Area quadrangles are done. The Sierra Nevada VTM surveys were mostly conducted around 1934, meaning that this dataset provides a potential for assessing change in vegetation over the past 60 years. The map analysis presented here covers the central and northern Sierra Nevada Mountains, which were mapped in both time periods, permitting the comparison.

There are several ways that these historic vegetation data can be used: vegetation plots can be revisited to see how tree size and the composition of species of trees at a particular location have changed. The plots in a region from different time periods can be summarized to describe the distribution of each tree species among different size classes, and then compared; and, the vegetation maps can be used to compare how much area was covered by different types of vegetation in each time period.

The Wieslander maps were compared to a modern digital vegetation map made by the US Forest Service in 1996 (Schwind and Gordon, 2001). Because the level of spatial detail in each map was different, a 300 m grid was created for the study area. Vegetation types occupying the most area were identified within each grid cell (about 500,000 cells for this study), and assigned to that cell. Once the dominant vegetation from each time period was identified for each cell, those cells which had been listed as ponderosa pine forest, but which had become a non-conifer vegetation type, were identified, and the pattern of loss at the lower edge was revealed.

The historical climate surfaces were available in a 1 km^2 format. A 40-year average of monthly values, from 1900 to 1940, and another average from 1980 to 2006 were used to identify weather conditions in two time periods that were relevant to the survey times of the two vegetation maps. The results were resampled into the same 300 x 300 m cells for which changes in vegetation had been identified. The average change in temperature and precipitation values between time-periods were calculated and biologically meaningful cutoff points were chosen, such as the freezing point of water, to see whether there were corresponding trends in vegetation change to those locations.

Strengths and Limitations of the Data

Historical reconstructions, whether of climate or vegetation, are dependent on the quality of the data. In the case of the Wieslander maps, the historic maps upon which the vegetation was surveyed have spatial inaccuracies of up to ~300 m. This is why changes were not identified at any finer grain size. However, the Wieslander Vegetation Type Map survey was one of the most complete and thorough efforts to document the forests of California. The use of these data is a unique opportunity. The general trend is consistent across the entire western flank of the Sierra Nevada, which also lends credence to the findings.

Future studies of the VTM and contemporary vegetation plot data will provide a second line of evidence for the occurrence of the conifer retreat. At the moment, all the recently published studies point to trends in the same direction.

The climate surfaces used are one (Parra and Monahan, 2008) of two historical climate reconstructions for California. The other one is the gridded climate data from Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1997). Comparison of these two studies will permit better understanding of what regions of the state one can really track climate change, and in what regions there is greater or less uncertainty in the maps. Generally, the high elevation zones of the Sierra Nevada are the least well represented by weather stations that could be used in the reconstructions. This study reports phenomenon more than two-thirds of the way down from the peaks of the Sierra, an area where there are more weather stations. Hence, while the historical climate maps of California as a whole may have some areas of high uncertainty, the region reported here was fairly well documented.

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For more information, contact:

UCDAVIS
UNIVERSITY OF CALIFORNIA
James Thorne
Department of Environmental Science and Policy
University of California Davis
2132 Wickson Hall, 1 Shields Avenue
Davis, CA 95616
(530) 752-4389
jhthorne@ucdavis.edu

Impacts on biological systems: Vegetation

ALPINE AND SUBALPINE PLANT CHANGES

TYPE II INDICATOR

Alpine environments are high mountain areas above the tree line, characterized by low, shrubby, slow-growing vegetation. Because the alpine environments are found at all latitudes, it is the only terrestrial biome where climate-induced changes along gradients in altitude, latitude and longitude can be compared globally.

Changes in alpine ecosystems are good indicators of climate change for a number of reasons, including the following:

- High altitude ecosystems at the low-temperature limits of plant life are generally considered to be particularly sensitive to climate change; hence, the effects of climate change may be more pronounced compared to ecosystems at lower altitudes.

- Alpine regions are relatively pristine and largely undisturbed by direct human influences. Climate change impacts can be distinguished in these regions with little or no masking due to effects caused by human land use.

- Most high mountain plants are long-lived species that are likely to show little response to transient variations in climate. However, a sustained change in climate is suspected to cause shifts in plant distributions and threaten their long-term survival.

Evidence of climate-induced upward migration of mountain plants has already been detected. Despite their long-lived and slow-growing nature, alpine vegetation and the distribution limits of its species do respond to climate change.

The *Global Observation Research Initiative in Alpine Environments*, also known as GLORIA (www.gloria.ac.at), is an international research network based in Austria. The purpose of the GLORIA Project is to establish and maintain a world-wide long-term observation network. The project utilizes a standardized protocol for monitoring and documenting alpine plant patterns for high mountain biodiversity and climate change. The protocol was developed by a network of international scientists in the late 1990s. Vegetation and temperature data collected at the GLORIA sites will be used for discerning trends in species diversity and temperature. The use of standardized methods and the global distribution of monitoring sites will allow the simultaneous study of climate induced impacts over all major life zones and climatic zones globally. Monitoring intervals are foreseen to be in the range of five to ten years. (Grabherr, 2005)

The GLORIA network is arranged globally along target regions, each of which comprises a mountain area with consistent regional climate and bedrock conditions. The global distribution of target regions is intended to reflect the relative areas of high mountain systems on each continent and to represent all major vegetation zones from polar to tropical latitudes. Between 2004 and 2006, four monitoring sites were established in California in target regions located in Dunderberg and in Carson Range/Tahoe Basin area in the Sierra Nevada, and in two areas in the White Inyo Mountains. Monitoring at these sites is carried out by the Consortium for Integrated Climate Research in Western Mountains, a collaborative, interdisciplinary consortium sponsored by a diverse group of agencies, universities and institutions, including the U.S. Forest Service Pacific Southwest Research Station, the U.S. Geological Survey, and the University of California White Mountain Research Station. Baseline inventories for the Sierra Nevada sites have identified 65 taxa and 18 families of plants.

In addition to target regions, GLORIA also includes “master sites,” designed to further develop and test field methods for long-term monitoring, to include other organism groups besides plants, and to carry out in-depth studies on region-specific ecological impacts. Two master sites have been established: Mount Schrankogel in the central high Alps of western Austria, in 1994; and the White Mountains of California, based on existing facilities of the University of California, in 2006. Although the California sites have been established within the past five years, results so far show some forest densification and colonization of formerly persistent snowfields and meadows as a response to temperature, without a significant change in treeline. There has been a general subalpine forest infilling such as at Tioga Pass, Mammoth Crest, and Mt. Warren.

Monitoring data collected at the California sites over the long term will allow for better characterization of climate change impacts on alpine and subalpine vegetation. At this time, sufficient data are not available to present status or trend information describing vegetation changes (when such data become available, this indicator will be presented as a “Type I” indicator).

Krumholz is a feature of subarctic and subalpine tree line landscapes, where continual exposure to fierce freezing winds causes vegetation to become stunted and deformed. The wind kills branches on the windward side, giving the tree a characteristic flag-like appearance. Where the lower portion of the tree is protected by snow cover, only the exposed upper portion has this appearance. Milder conditions favor persistence of flags and growth of upright stems at the upper portion of the tree. There is some evidence that trees are having a more moderate response to the Krumholz effect due to less harsh conditions. (Millar, 2006a; b)

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For more information, contact:

CIRMOUNT
Consortium for Integrated Climate Research in Western Mountains
www.fs.fed.us/psw/cirmount
Anticipating Challenges to Western Mountain Ecosystems and Resources

Constance Millar
800 Buchanan Street
West Annex Building
Albany, CA 94710-0011
P.O. Box 245
Berkeley, CA 94701-0245
(510) 559-6435

Impacts on biological systems: Vegetation

WINE GRAPE BLOOM

TYPE II INDICATOR

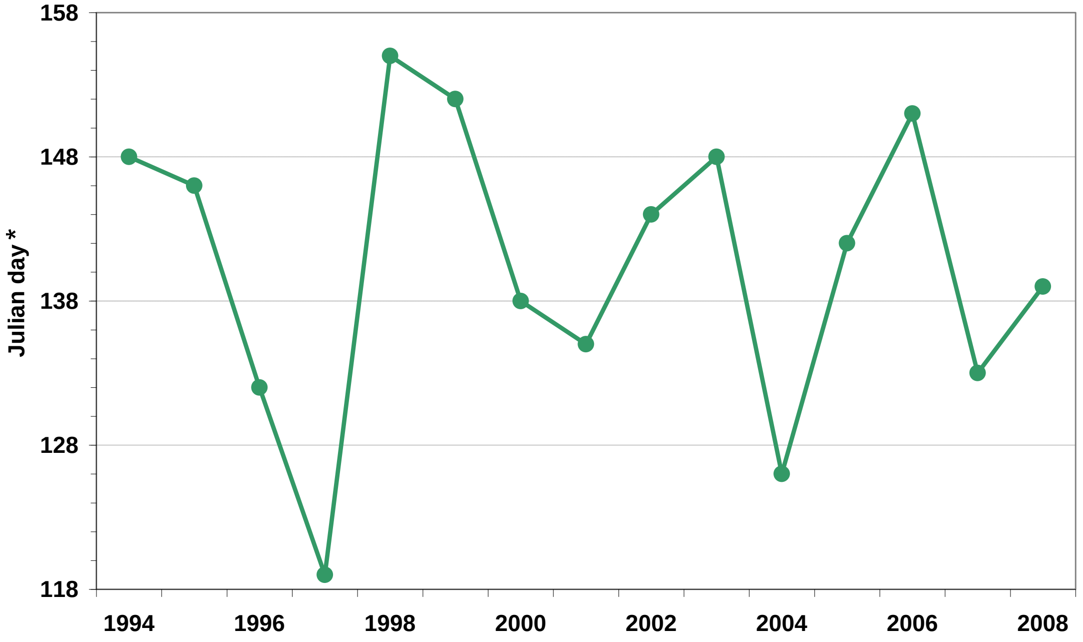
Observations regarding changes in the timing of seasonal events in crops – specifically perennial crops which are less dependent on planting, cultivation and other agricultural management decisions -- provide important evidence of responses to recent regional climate change. In particular, winegrapes are known to be highly sensitive to climatic conditions, especially temperature (IPCC, 2007). Wine grapes respond more directly to long-term climatic variations than more intensely managed crops, because they are less irrigated and fertilized, minimally genetically engineered, and long-lived (Nemani et al., 2001).

The climate sensitivity of wine grapes has made grape harvest dates a proxy to reconstruct climate in France back to the 1300s (Chuine et al., 2004). Grapevine developmental stages include bud break, flowering or bloom, fruit set, veraison (color change and beginning of maturation), harvest (when fruits are fully mature) and leaf fall. The timing and pace by which vines go through these stages have been related to the size of the yield, and the quality of the vintage (Nemani et al., 2001).

The first stage, bud break or budburst, is marked by the emergence of new leaves as the vines break from their dormant winter period. Budburst in most regions occurs when the mean daily temperature is above 10°C (50°F) for five consecutive days (Mullins et al., 1992). Bloom, the second major phenological stage for wine grapes, is highly influenced by climate conditions, occurring most rapidly when climate conditions reach 18-21°C (64-70°F) (Winkler et al., 1974). Bloom refers to the flowering of the scores or hundreds of individual flowers on each cluster. It typically occurs approximately six to eight weeks after budburst, and under favorable weather conditions, lasts 8-10 days. Bloom is important for determining the number of berries per cluster and plays an important role in determining overall yields. As a general rule, bloom is typically followed 6-8 weeks later by the third stage, veraison, which is followed 6-8 weeks later by harvest. Thus, bloom often occurs around 100-110 days before harvest (Cahill, 2008).

Bloom is relatively easy to observe, and is highly temperature-sensitive, making it a good indicator of wine grape phenological response to changes in climate. However, long-term data on the timing of wine grape bloom in California's Napa and Sonoma Valleys, the area recognized for producing some of the best wines in the United States, have been difficult to obtain. Further, each grower often has a preferred method for recording phenological stages in vineyards, making comparisons and aggregation of data difficult. The graph below presents data on one grape variety in one vineyard in one region; data would be strengthened by adding information from other varieties and regions (Cahill, 2008). Although the net difference in bloom dates when comparing 1994 with 2008 is 10 days, the fluctuations/variability in the data points during the 14-year period compromise the ability to demonstrate a clear trend. Researchers conducting ongoing monitoring of bloom dates at this vineyard will allow further characterization of wine grape development and climate-related trends.

Pinot Noir Bloom
Saintsbury Home Ranch, Napa side of Carneros



Source: Cahill, 2008

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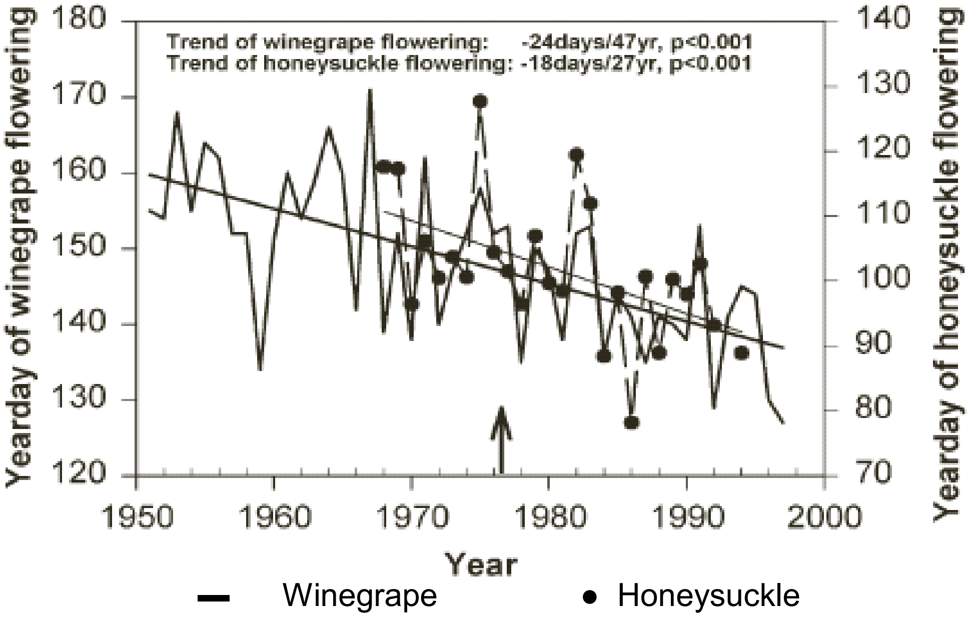
* Julian day is a system of numbering days consecutively (instead of by cycles of days such as weeks or months), with January 1 as the first Julian day, and December 31 as the 365th Julian day (or the 366th day of a leap year).

Nemani et al. (2001) estimated wine-grape flowering dates in the Napa and Sonoma Valleys for 1951-1997. These estimates were based on accumulated “growing degree days,” a metric calculated based on the number of days and the accumulated heat units above a base temperature of 10°C. Bloom was estimated to occur when 425 growing degree-days were reached starting from January 1st of each year. The graph below shows a 24-day advancement of the estimated flowering dates between 1951 and 1997. Also shown are observed honeysuckle flowering dates from 4 sites in the Napa and Sonoma Valley region from 1968-1994, and how they correlate with the wine-grape estimated flowering dates. The researchers attribute this earlier flowering phenomenon to observed winter and spring warming trends in the region. Research is currently underway to examine historical records of bloom and see how they correspond to this modeled estimate.

Estimated wine grape flower dates



Source: Nemani, et al., 2001

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For more information, contact:

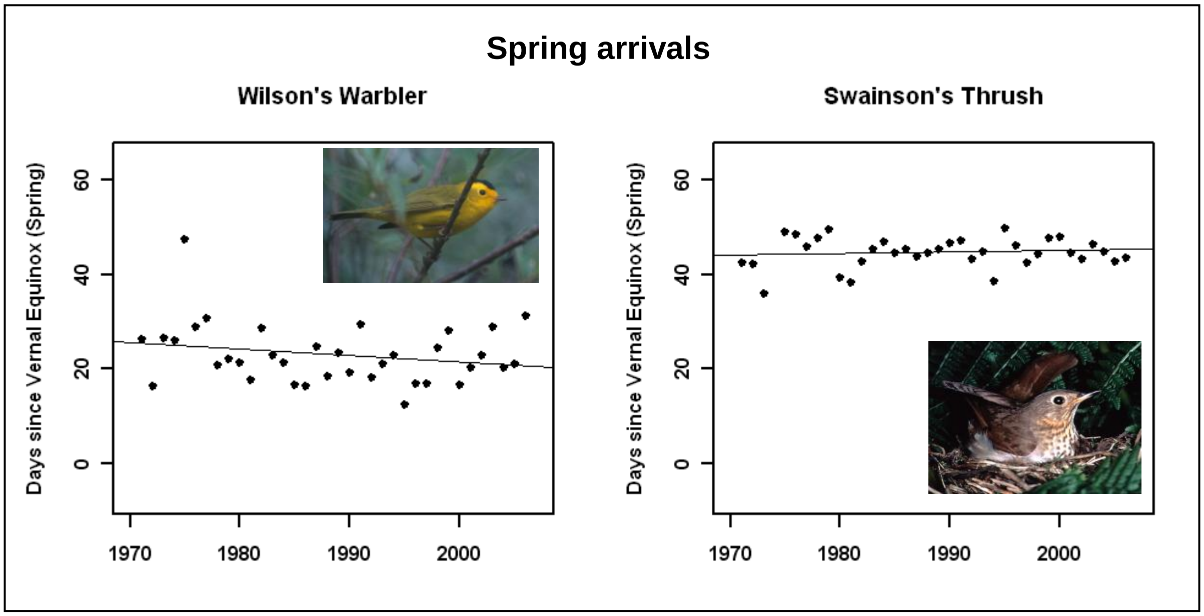
Kim Nichols Cahill
Department of Global Ecology
Stanford University
260 Panama Street
Stanford, CA 94305
(415) 279-2379
kncahill@stanford.edu

Dan Cayan
Climate, Atmospheric Sciences, & Physical Oceanography Research Division, Scripps Institution of Oceanography, UCSD
and
Water Resources Discipline, US Geological Survey
201 Nierenberg Hall
La Jolla, CA 92093-0224
(858) 534-4507
dcayan@ucsd.edu

Impacts on biological systems: Animals

MIGRATORY BIRD ARRIVALS

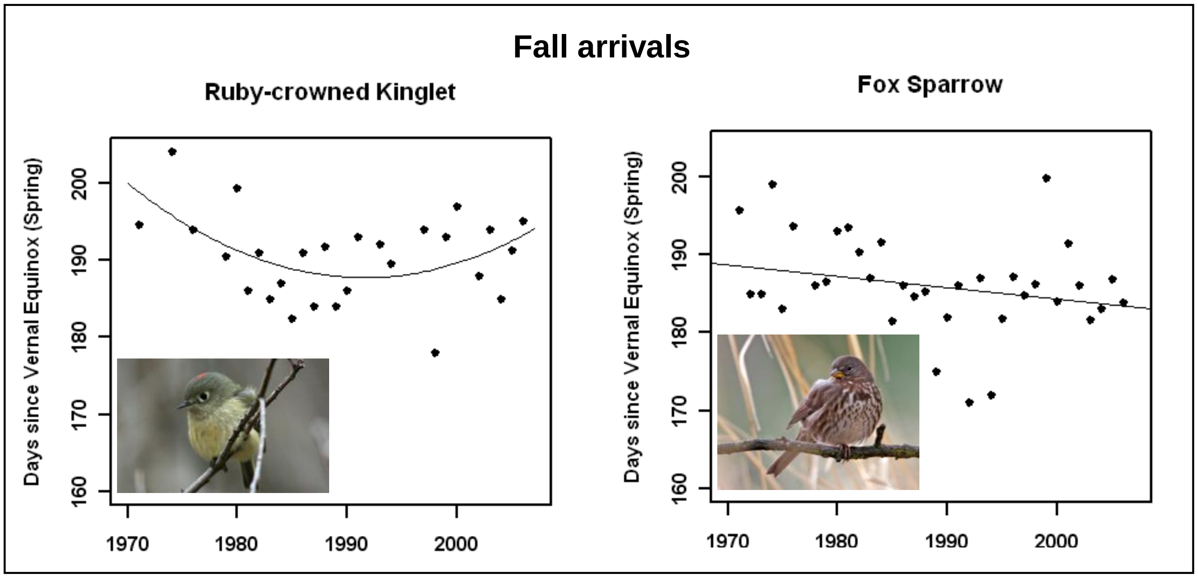
Spring and fall arrivals of some migratory birds are changing.



Spring arrivals

Wilson's Warbler

Swainson's Thrush



Fall arrivals

Ruby-crowned Kinglet

Fox Sparrow

Source: PRBO, 2008

Photo credits: Rich Stallcup, PRBO (Wilson's Warbler); Ian Tait, PRBO (Swainson's Thrush); Rick Lewis, PRBO (Ruby-Crowned Kinglet); Tom Munson (Fox Sparrow)

What is the indicator showing?

Trends in spring and fall arrival dates of birds migrating to their breeding (spring) and wintering (fall) grounds in Northern California vary among species. Over a 36-year period at the Point Reyes Bird Observatory's (PRBO) Palomarin Field Station on Point Reyes Peninsula, Wilson's Warblers (*Wilsonia pusilla*) have been arriving significantly earlier in recent years, a pattern shown by several other songbird species (MacMynowski et al., 2007). In contrast, spring arrival dates of Swainson's Thrushes (*Catharus ustulatus*) have been remarkably stable. Fall arrivals of Ruby-crowned Kinglets (*Regulus calendula*) from more northerly breeding grounds show a significant fit to a quadratic regression, arriving earlier from 1971 until the mid 1980s, then reversing to arrive later in the fall. Fox Sparrows (*Passerella iliaca*) show a significant long-term trend toward earlier fall arrival dates. Arrival dates for all species vary from year to year, so trends are only apparent with long-term data.

Why is this indicator important?

Evidence from studies of regional climate effects on terrestrial species shows consistent responses to warming trends. Among the responses observed is a change in the timing of migration across the Northern Hemisphere. Records of the return dates of migrant birds have shown changes in recent decades associated with changes in temperature in wintering or breeding grounds, or on the migration route (Gordo, 2007; IPCC, 2007; MacMynowski et al., 2007).

This indicator illustrates the value of long-term data, gathered in a systematic way, in revealing trends in spring and fall arrival dates of migratory songbirds. It adds California-specific observations to the growing body of data describing temporal patterns in bird migration. Such regional information helps improve the scientific understanding of factors that may be influencing the timing of migration and how these factors may be reflected in global trends, as well as how they vary regionally.

What factors influence this indicator?

The graphs above show clearly that different species are showing different patterns. The early arrival of some spring migrants at Palomarin is expected. Earlier arrival of spring conditions (and, consequently, available breeding habitat) has been documented over much of the Northern Hemisphere (Root et al., 2005; Parmesan, 2006; for review see Gordo, 2007). In contrast, less research has been performed on fall arrival of birds to their wintering grounds. Expected trends in fall arrival are less intuitive. Warmer summers may improve breeding conditions in the arctic and allow longer breeding seasons, or species might increase breeding effort and consequently delay migration to wintering grounds. Alternatively, individuals that arrive earlier on the breeding grounds in spring may complete breeding earlier and initiate fall migration earlier. Other factors, such as the phenology of forage/prey or increased inclement weather, may restrict breeding season length, forcing species to leave and arrive on wintering grounds earlier.

Environmental conditions in the wintering or breeding grounds, on the migration route, or on the final settling location, all of which affect arrival times, may in turn be affected by factors operating on multiple spatial scales. The variety of factors and the multiplicity of temporal and spatial scales at which birds operate during migration undoubtedly contribute to the considerable inter-annual variation in arrival dates.

Broad-scale Climate Indices

Broad-scale hemispheric or continental indices can be used to provide a quantitative categorization of regional climate conditions that a species may respond to throughout the entire species' distribution (e.g., Root et al., 2003; MacMynowski et al., 2007). These climatic conditions can directly influence a species' collective decision to initiate migration. Examples include North Atlantic Oscillation, Pacific Decadal Oscillation and El Niño Indices such as the Multivariate El Niño Index and Southern Oscillation Index.

Regional Conditions

Migrating birds respond strongly to atmospheric pressure cells and the passage of fronts, which can accelerate or hold back their migratory movements. Within a given year, the arrival date of a species may depend on the proximate occurrence of weather patterns on the migratory route.

Local Conditions

Local weather conditions, such as recent rainfall and temperature, can create unique local breeding conditions that vary from place to place across the landscape. These conditions may influence whether individual birds remain within the area of study and are available for capture.

Habitat Trends

Birds are not undertaking migratory movements within a static environment. The vegetation communities that are the template for songbird habitat in terrestrial ecosystems are continuously changing. These changes are driven by normal ecological succession processes and, more recently, changes in land use and climate change. These forces result both in shifts in vegetational phenology (and consequent shifts in the emergence and abundance of invertebrate prey of birds) and in plant distributions across climate gradients (such as elevation).

Technical Considerations:

Data Characteristics

Data type - The raw data for this analysis consist of records of individual birds banded in mist nets using a standard protocol (Ralph et al., 1993). The Palomarin Field Station is in north-central coastal California, near the southern end of the Point Reyes peninsula, within Point Reyes National Seashore (37°56´ N, 122°45´ W). Continuous data collection began in 1971. In general, sampling effort has remained relatively stable, although inclement weather can restrict survey efforts.

Data used for analysis –Only those birds known to be in their second year or greater (i.e., after-hatch-year) are included. The species selected for this analysis were chosen for their documented sensitivity to climate and weather (MacMynowski et al., 2007; PRBO unpublished data) and high capture rates. For the analysis of spring arrivals, the five most frequently captured species that are expected to be responsive to climate and weather in the spring were selected: Black-headed Grosbeak (*Pheucticus melanocephalus*), Warbling Vireo (*Vireo gilvus*), Wilson's Warbler, Swainson's Thrush, and Orange-crowned Warbler (*Vermivora celata*). Fall species selected are Goldencrowned Sparrow (*Zonotrichia atricapilla*), Fox Sparrow, Ruby-crowned Kinglet, and Yellow Warbler (*Dendroica petechia*). The graphs illustrate species for which there were significant trends.

Response Variable – Within each year only the first quartile (25%) of captures for each species was used in this analysis. This increased the probability that birds captured and used in the analysis were birds that had recently arrived at the location. Within this subset of the data, the mean date of capture was used as the estimated arrival date for the species. Mean arrival date can remove bias associated with a trending population size (Miller-Rushing et al., 2008). In order to remove bias that changes in timing of actual spring (vernal equinox) can have on Julian or calendar dates (Sagarin, 2001), see Miller-Rushing et al., 2008), arrival date were transformed to "days since vernal equinox."

Strengths and Limitations of the Data

These data provide a long-term record of bird migration phenology. Monitoring efforts have been strictly standardized since 1979; they were less rigidly standardized from 1971-1978.

Effects of change in effort or population size – A change in monitoring effort was expected to produce a similar bias to that of change in population size of a species. It has been shown previously that population sizes can affect first arrival dates (Miller-Rushing et al., 2008). By using mean arrival date of the first quartile of captures, the impact that population size can have on arrival distribution is reduced.

Location is terminus of migration – Because the Palomarin Field Station is not a location along the migratory pathway for all the individuals captured of these species but rather is the final stopping location (either for breeding or wintering) for some to many of them, depending on the species, it is possible to bias results toward later dates, because there is increased probability that birds being captured have been present at the location for some period of time. We have attempted to minimize this by restricting our analyses to the initial 25% of all captured birds.

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For more information, contact:

Mark Herzog, Ph.D.
PRBO Conservation Science
3820 Cypress Dr. #11
Petaluma, CA 94954
(707) 781-2555 ext 308
mherzog@prbo.org
(707) 781-2555 ext 308
mherzog@prbo.org

John Wiens, Ph.D.
PRBO Conservation Science
3820 Cypress Dr. #11
Petaluma, CA 94954
(707) 781-2555 ext 3
jwiens@prbo.org

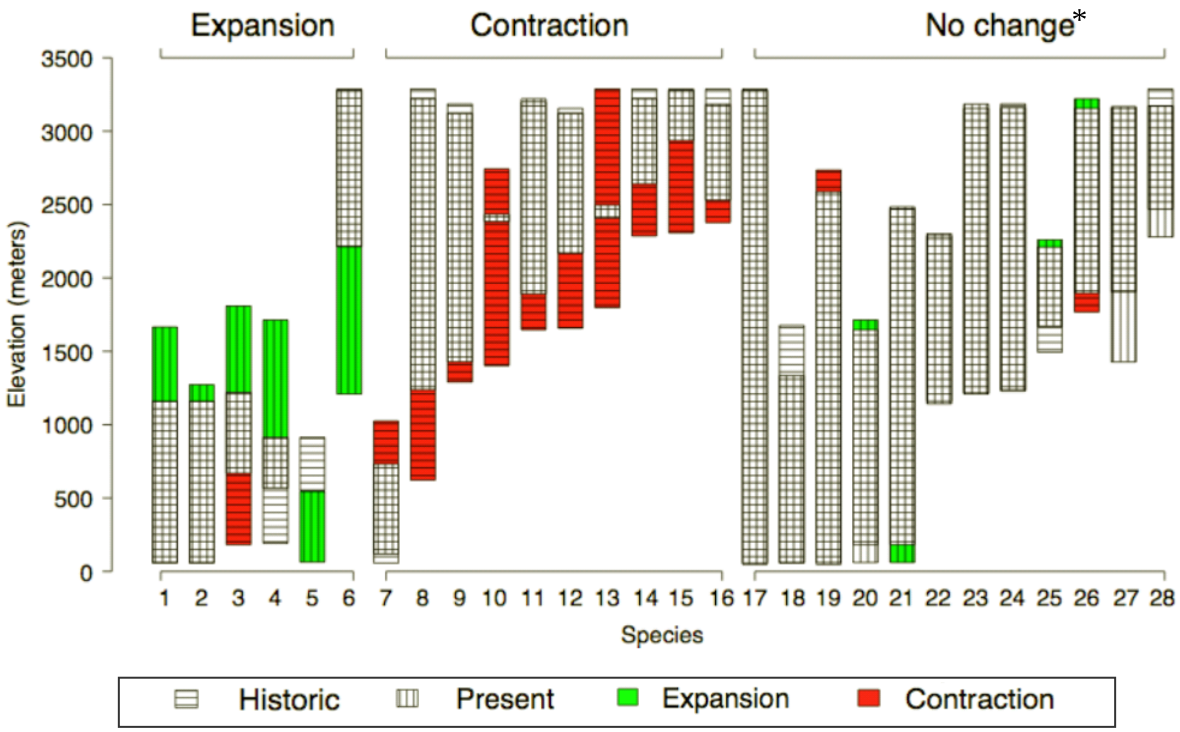
Diana Humple
PRBO Conservation Science
Palomarin Field Station
PO Box 1157
Bolinas CA 94924
(415) 868-0655 x386
dhumple@prbo.org

Impacts on biological systems: Animals

SMALL MAMMAL RANGE SHIFTS

About half of the species surveyed in Yosemite National Park show a change in the elevation at which they can be found today, compared to earlier in the century; most of these changes involved movement to higher elevations, by an average of approximately 500 meters. Range expansions generally occurred among species historically found at lower elevations, while most contractions (i.e., reductions in elevational range) occurred among mid- to high elevation species.

Shifts in elevational range of small mammals, Yosemite National Park
Historic (1911-1920) vs. Present (2003-2006)



Species:
1. *Microtus californicus* (California vole)
2. *Reithrodontomys megalotis* (Western harvest mouse)
3 *Peromyscus truei* (Piñon mouse)
4. *Chaetodipus californicus* (California pocket mouse)
5. *Sorex ornatus* (Ornate shrew)
6. *Sorex monticolus* (Montane shrew)
7. *Dipodomys heermanni* (Heerman’s kangaroo rat)
8. *Microtus longicaudus* (Long-tailed vole)
9. *Zapus princeps* (Western jumping mouse)
10. *Tamias senex* (Allen’s chipmunk)
11. *Spermophilus lateralis* (Golden-mantled ground squirrel)
12. *Sorex palustris* (Water shrew
13. *Neotoma cinerea* (Bushy-tailed woodrat)
14. *Spermophilus beldingi* (Belding’s ground squirrel)
15. *Tamias alpinus* (Alpine chipmunk)
16. *Ochotona princeps* (American pica)
17. *Peromyscus maniculatus* (Deer mouse)
18. *Thomomys bottae* (Botta’s pocket gopher)
19. *Spermophilus beechyi* (California ground squirrel)
20. *Neotoma macrotis* (Big-eared woodrat)
21. *Peromyscus boylii* (Brush mouse)
22. *Sorex trowbridgii* (Triowbridge’s shrew)
23. *Mictous montanus* (Montane vole)
24. *Tamiasciurus douglasii* (Douglas squirrel)
25. *Tamias quadrimaculatus* (Long-eared chipmunk)
26. *Tamias speciosus* (Lodgepole chipmunk)
27. *Thomomys monticola* (Mountain pocket gopher)
28. *Marmota flaviventris* (Yellow-bellied marmot)

Source: Moritz et al., 2008

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* No change” includes changes <5 percent of the range or <100 meters, which are considered biologically trivial.

What is the indicator showing?

The indicator summarizes changes in the elevational range of small mammals across Yosemite National Park and adjacent areas. It presents a comparison between (a) the historical elevation ranges where species were detected during a survey conducted between 1911 and 1920, and (b) present-day ranges based on a recent resurvey of the same field sites. No change in range was seen in 12 of the species (this includes species for which changes are less than 5 percent of the range, or 100 meters, which are considered biologically trivial). Among the species that showed a change, more species were found to have contracted elevation ranges (i.e., a reduction or narrowing in the elevational range where they were found), than species with expanded ranges. Four of the species with expanded ranges moved towards higher elevations; two species expanded toward lower elevations. Range contractions mostly involved an upward movement of the lower limit where the species were previously found, and two species showing a contraction in both their lower and upper elevational limits, i.e., a range collapse.

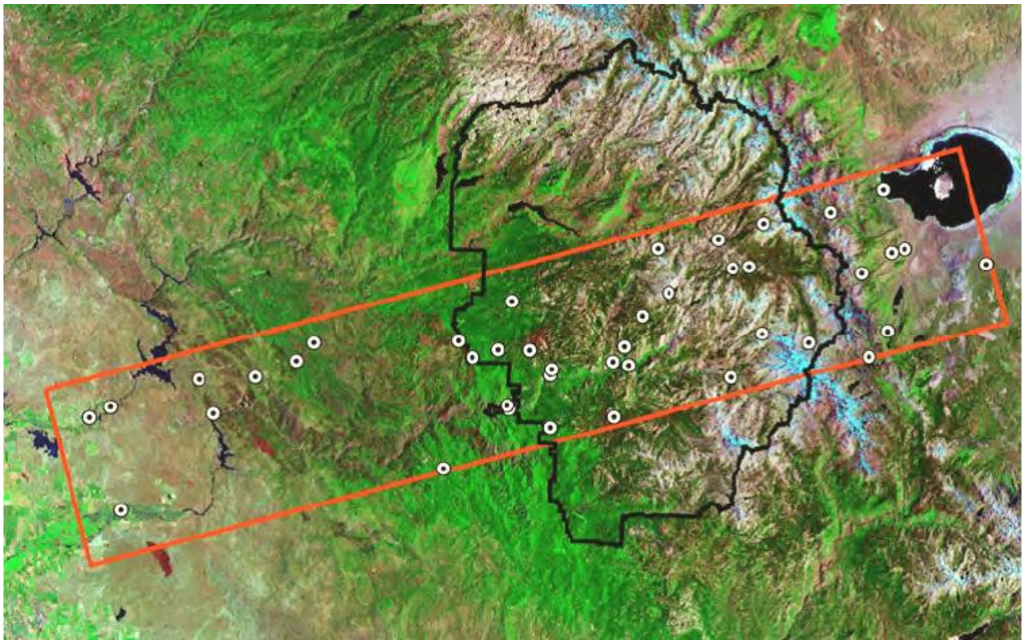
Why is this indicator important?

This indicator is based on a study of species distributions and habitat and community changes over the past century in an area that stretched from the western foothills of the Sierra Nevada, through Yosemite National Park, to the area around Mono Lake (see map on the next page). The study (hereinafter referred to as the “Grinnell Re-survey”) surveyed terrestrial vertebrates at 21 sites in Yosemite National Park that had been the original field sites surveyed by Joseph Grinnell and a team of scientists from the University of California at Berkeley’s Museum of Vertebrate Zoology between 1911 and 1920. This earlier survey – along with the collected specimens, field notes and photographs --provides much of the knowledge of the vertebrate fauna of the Park, and serves as an important baseline against which changes in faunal over time can be compared (Moritz et al., 2008). The Yosemite transect is one of several across the Sierra examined by Grinnell and colleagues in the early 20th century and the Grinnell Resurvey project is progressively re-examining ranges of small mammals and birds across several of these (see http://mvz.berkeley.edu/Grinnell/index.html). By extending the analyses to these other transects (e.g., Lassen, Tahoe, southern Sierra), which have experienced different magnitudes of climate and land-use change over the past century, it should be possible to tease apart the multiple factors that cause range shifts.

Animals reproduce, grow and survive within specific ranges of climatic and environmental conditions. Species may respond to changes in these conditions by, among other things, a shift in range boundaries (IPCC, 2007). The indicator presented here tracks changes in the elevation at which species are currently found, and compares these with records from earlier in the century. This information will help in understanding and anticipating the long-term dynamics of the distribution of vertebrates in California, and examining the factors that influence them. This knowledge is crucial in efforts to identify which species are resilient or sensitive to climate change and, thus, to guide efforts to maintain species diversity in the face of regional warming. In addition, the data will be used to test the performance of model-based predictions of species’ responses to changes in climate and land-cover, and thereby improve on predictions of future responses. The range contractions so far observed, which mostly involved higher elevation species such as the Bushy-tailed woodrat, Pika, and Alpine chipmunk, are of particular concern, given the decreased habitat area at higher elevations. Allen's chipmunk and the Western slope bushy-tailed woodrat showed bidirectional range contractions – i.e., an increase in the lower limit and decrease in the upper limit of their elevational range – that represented a reduction of their historical range by more than 90 percent (Moritz et al., 2008).

The Grinnell Yosemite Transect (red rectangle)

The 41 original sites surveyed (1911-1920) are shown as white circles with black centers. Yosemite National Park is outlined in black.



Source: Moritz et al., 2007

What factors influence this indicator?

Although analyses of spatial patterns of change and contributing factors are still underway, some general observations can be made. There have been substantial vegetation changes within Yosemite National Park since the Grinnell Period, due to a number of factors including fires, fire suppression efforts, and temperature changes. Vegetation change appears to directly affect some of the changes in the range of small mammals. For example, the expansion of the upper limit of the ranges of the California pocket mouse and the Piñon mouse (on the west slope) can be attributed to stand-replacing fires in the lower areas of the park. The large downwards shift in the elevation of the Montane shrew is probably related to its preference for wet meadows and the recovery of wet meadow systems in Yosemite Valley, following cessation of grazing and intense restoration efforts.

The magnitude of temperature changes across the study sites is difficult to establish because long-term records are sparse. Nevertheless, the Yosemite Valley record indicates a substantial increase in monthly minimum temperatures, (i.e., >3°C; this temperature increase is also evident from tree ring data and analyses of vegetation change (Millar, 2004), snowmelt data, and retraction of the Mt. Lyell glacier. Warming temperatures may have resulted in some expansion of conifer forests and invasion of meadows at high elevations. In addition to impacting vegetation, increased temperatures have also been identified as a likely cause of the contractions of the high-elevation species and at least some of the upwards expansions of lower elevation species. In fact, the average increase in lower and upper limits of 500 to 600 meters observed in the re-survey is consistent with what would be expected with the observed temperature increase of 3°C, assuming that the species ranges are limited primarily by physiology. Other factors also could be at play, including community structure and competitive interactions, given the variable responses among related species.

Technical Considerations:

Data Characteristics

The data shown here are from a re-survey of terrestrial vertebrate fauna (mammals, birds, reptiles, and amphibians) conducted from 2003 through 2006. As mentioned earlier, this recent survey revisited the 21 sites within Yosemite National Park that were originally studied between 1911-1920 by Joseph Grinnell and other staff of the Museum of Vertebrate Zoology (MVZ), University of California at Berkeley. The resurveys provide updated information on habitat and community changes at each site over the past century, while documenting the presence as well as ranges (geographic and habitat) of species of special concern to the Park and to the lay and scientific communities.

In addition to the Yosemite Transect described earlier, other resurvey sites include the Lassen Transect, the Warner Mountains Transect, the White Mountains Transect, and the San Jacinto Transect. Additional information on these sites can be found at: http://mvz.berkeley.edu/Grinnell/index.html. The resurveys focus on both small mammals and birds – preliminary analysis of bird distributions echo the results presented above for small mammals (M. Tingley and S. Beissinger, personal communication).

Original field notes and maps archived at MVZ were used to identify the original field sites. Field teams spent a minimum of ten days at each site, and sampled each of the major habitats within a radius of approximately 1 kilometer. Most sites were surveyed once during the three-year period, although several were revisited two or more times. For details of the trapping methods employed, see Moritz (2007).

Strengths and Limitations of the Data

Detailed maps and field notes from the Grinnell investigators facilitated the relocation of actual sites, transects and trap lines. The position of all generalized sites, based on documentation of the actual campsite, has been reasonably well established.

Substantial differences in survey methodologies between the two survey periods may result in biases in trapability. The Grinnell team used shotguns and snap traps for all mammal surveys, while the recent survey used live traps. To assess the comparability of survey success for each species across the time periods, statistical ("Occupancy") analyses were conducted. For the 28 species of small mammals considered above, detectability probabilities were sufficiently high across the two survey periods to yield robust results. The analysis of changes in elevational range of mammals incorporates differences in detectability between study periods.

Finally, natural year-to-year fluctuations in species' abundances may affect the detection of particularly rare species, and hence the comparisons between the two study periods.

Resurveys of the small mammal communities across the four Sierra Nevada transects, and some adjacent areas (White Mountains, MVZ; San Jacinto transect, San Diego Museum of Natural History) will be completed in 2010, and the avian resurveys of the Sierra transects in 2009. Beyond that, avian resurveys of coastal woodlands, from Mendocino to Monterey counties, and stratified across different degrees of climate and land-use change, are planned for 2009-2010. There is potential to further expand avian resurveys through collaborative "citizen-science" projects.

These resurveys are intensive, and for small mammals in particular, are most informatics on multi-decadal timescales; e.g., they could be repeated in 2040-2050 to test general predictions that will come from forecast models. The current project already has identified several high elevation species of immediate concern that could be the focus of more extensive resurveys and multi-year demographic monitoring.

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For more information, contact:

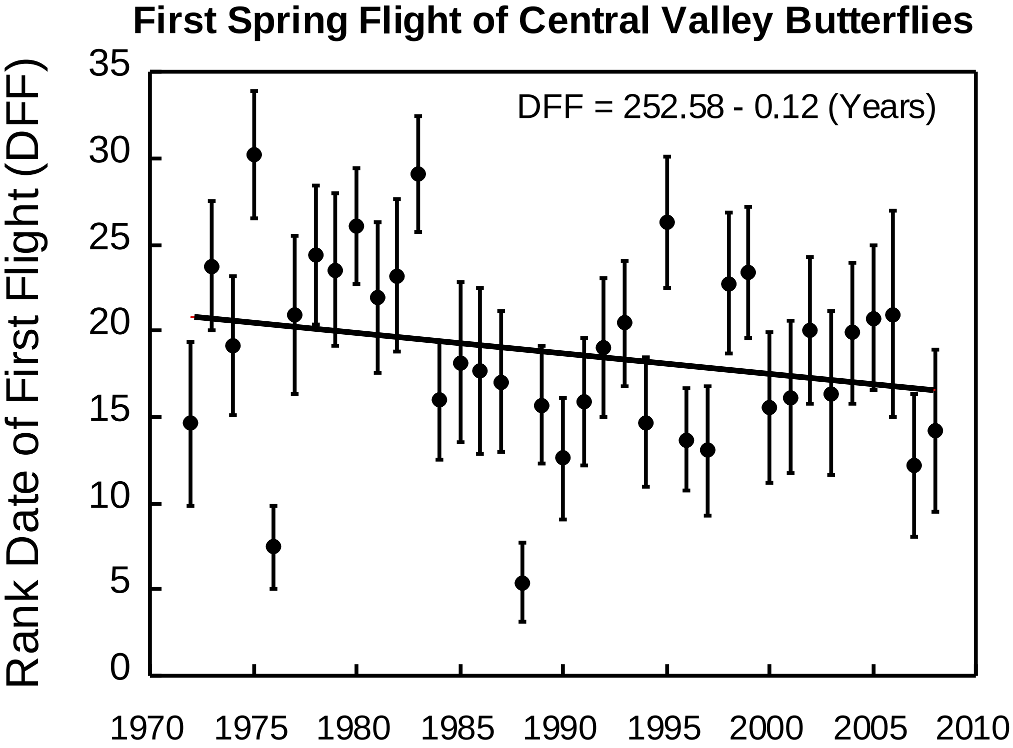
Craig Moritz, Ph.D.
University of California, Berkeley
Museum of Vertebrate Zoology
3101 Valley Life Sciences Building
Berkeley, CA 94720-3140
(510) 643-7711
craigm@berkeley.edu

Impacts on biological systems: Animals

SPRING FLIGHT OF CALIFORNIA CENTRAL VALLEY BUTTERFLIES

Over the past 37 years, common butterfly species have been appearing in the Central Valley earlier in the spring.

Painted lady (*Vanessa cardui*)
Photo: Jim Ellis



Source: Updated from Forister and Shapiro, 2003

What is the indicator showing?

The average date of first flight (DFF) of a suite of 23 butterfly species in the Central Valley of California has been shifting towards an earlier date in the spring over the course of the past 37 years. The DFF refers to the date that the first adult of a species is observed in the field in a given calendar year. The graph displays the trend in DFFs for the 23 species collectively as the “rank date of first flight,” derived as follows. For each species, the DFFs across years were ranked from 1 to 37 (the number of years for which observations are available), with the earliest DFF receiving the rank of one. A value of 15 on the y-axis, for example, indicates that that particular year was on average the 15th earliest year across all species (errors bars shown on the graph represent 95% confidence intervals).

Why is this indicator important?

This indicator demonstrates the utility of common butterfly species for studying the biological impacts of a shifting climate. Plants and animals reproduce, grow and survive within specific ranges of climatic and environmental conditions. Changes in these conditions beyond a species' tolerances can elicit a change in phenology, or the timing of seasonal life-cycle events, such as leaf unfolding, flowering, bird migration, egg-laying and the appearance of butterflies. Many studies have investigated the relationship between phenology and changes in climate conditions. These studies, however, have largely been from higher, cool temperate latitudes, where minor climatic changes can have large impacts on species that are often at the limits of their ranges. By contrast, species from lower latitudes, where the climate is highly variable, with large fluctuations in temperature and precipitation, might be expected to be adapted to such variability. Hence, species in areas with Mediterranean climates such as California might be presumed to be less likely to respond to relatively subtle changes in climate conditions.

The shifting phenology of these 23 butterfly species is correlated with the hotter and drier conditions in the region in recent decades (U.S. EPA, 1997; Forister and Shapiro, 2003). The data supporting this indicator show that Central Valley butterflies are not only responding to changing climate conditions, but also that their response has been similar to butterflies from the more northern climate of England. This indicator complements similar studies from Europe and demonstrates the apparently ubiquitous phenological response of spring butterflies to warming and drying conditions (Roy and Sparks, 2000; Peñuelas et al., 2002). It is also worth noting that the Central Valley has also undergone intense land conversion, both to urban development and to agriculture. Thus, the data indicate that the phenological impacts of climate change are not restricted to northern latitudes or to pristine ecological conditions.

What factors influence this indicator?

Climatic conditions have a significant impact on the phenology of butterflies. Butterflies in the temperate latitudes enter a dormant state during the winter months; in the spring, temperature cues cause them to hatch, to resume feeding, or to emerge from pupae as adults (Dennis, 1993; Shapiro, 2007). As climatic conditions during key times of the year have changed, the timing of butterfly life-history events has undergone a corresponding change. The butterfly species monitored overwinter in different life history stages: as eggs (1 species), larvae (8 species), pupae (9 species) and adults (3 species); two of the species immigrate in the spring from distant over-wintering sites.

Statistical analyses to determine the correlation between DFF and twelve different weather variables show winter conditions – specifically winter precipitation, average winter daily maximum temperature, and average winter daily minimum temperature -- to have the strongest associations with the date of first flight.

While the collective response of the Central Valley butterflies is a relatively simple and statistically significant pattern of earlier adult emergence through time, differences in species-specific responses require further investigation. For example, of the 23 species studied, earlier emergence was observed for 16 species, with trends for 5 of the species being statistically significant. However, the opposite pattern – that is, later emergence -- was observed for 7 species. Two of these species have been emerging significantly later through time (the trends are highly statistically significant); these are also species with multiple generations per year (such species are known as “multivoltine”), and which are experiencing regional declines in abundance (Shapiro, 2007). As a multivoltine species becomes less abundant, the first generation may be missed by observers, thus the species may appear to be emerging later and later each spring. (For further discussion of relevant biological complexities, see Shapiro, 2003; Thorne et al., 2006).

Other factors may impact the phenological observations described here, such as nectar and host plant availability. Plant resources may in turn be affected by habitat conversion, though it is not obvious how these factors could lead to the earlier emergence of a fauna. Thus DFF seems to be a relatively simple and effective measure of an organism’s response to shifting climatic conditions.

Technical Considerations:

Data Characteristics

The data described here consist of the date of first spring adult flight (DFF) for 23 butterfly species. These were first reported by Forister and Shapiro (2003). Six years of data have been added to that original data set. The primary result remains unchanged by the updated data. In fact the slope of the regression shown in the graph is nearly identical to the slope from the earlier data set.

The species included in the data are as follows: *Atalopedes campestris*, *Erynnis tristis*, *Hylephila phyleus*, *Pholisora catullus*, *Polites sabuleti*, *Pyrgus communis*, *Pyrgus scriptura*, *Everes comyntas*, *Lycaena helloides*, *Plebjus acmon*, *Srtymon melinus*, *Danaus plexippus*, *Nymphalis antiopa*, *Phyciodes campestris*, *Phyciodes mylitta*, *Vanessa annabella*, *Vanessa atalanta*, *Vanessa cardui*, *Colias eurytheme*, *Euchloe ausonides*, *Pieris rapae*, *Papilio rutulus*, and *Papilio zelicaon*.

The study area is located in the Central Valley portions (below 65m elevation) of three Northern California counties: Yolo, Sacramento, and Solano. Three permanent field sites in these counties are visited by an investigator at two-week intervals during “good butterfly weather.” Most of the observations (> 90%) of DFF come from those permanent sites; however, if a butterfly was observed in a given year to be flying first at a location within the three counties but outside of the permanent sites, that observation is included as well.

In addition to the collective analyses discussed here, data for all species were also analyzed individually, both for trends in DFF through time and for correlations between DFF and weather variables. Weather data were obtained from the University of California/National Oceanic and Atmospheric Administration climate station in Davis, California, a World Meteorological Organization station centrally located among the study sites. Weather variables are not independent, and some were excluded as redundant before use in multiple regressions or other analyses.

Strengths and Limitations of the Data

Since the data are collected and compiled entirely by one observer (Arthur Shapiro), any biases in data collection should be consistent across years. This would not be true in studies which involve multiple workers -- with variable levels of training -- across years.

The primary limitation of the data stems from the fact that a quantitative connection between DFF and other species- or population-level dynamics has not been established. For example, if the spring phenology of a species shifts, does this affect the total flight window? Does it affect peak or total abundance throughout the season? As noted above, changing abundance has the potential to alter the probability of observation and thus the apparent DFF. The investigators are currently exploring this issue statistically using the data reported here, along with data on observations of abundance. Finally, the impacts that a shifting insect phenology may have on other species at higher and lower trophic levels, including larval hosts and predators, are also unknown.

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For more information, contact:

Matthew L. Forister
Department of Biology
University of Nevada Reno
Mail Stop 314
Reno, NV 89557
(775) 784-4053
mforister@unr.edu

Arthur Shapiro
Department of Evolution and Biology
University of California Davis
6347 Storer Hall
Davis, CA 95616
(916) 752-2176
amshapiro@ucdavis.edu

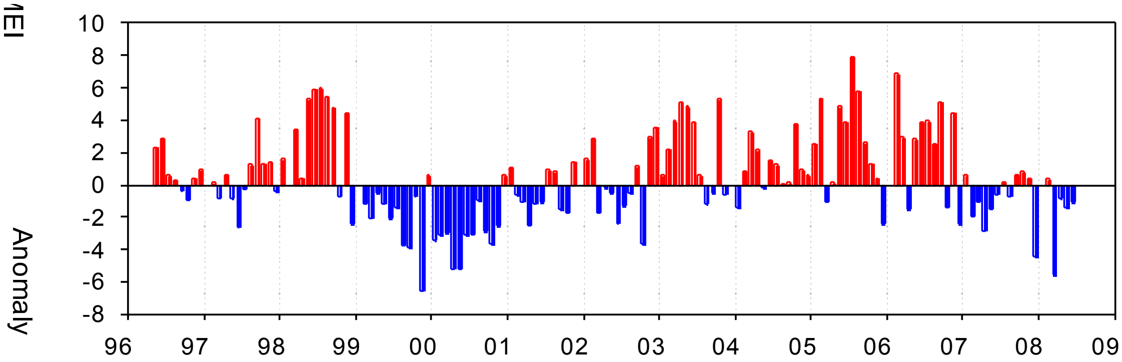
Impacts on biological systems: Animals

COPEPOD POPULATIONS

Variations in copepod populations in the Northern California Current ecosystem reflect large-scale changes in ocean circulation patterns.

Copepods are small marine crustaceans that comprise a large and diverse group of species that are a major food source for fish, whales, and seabirds. Copepods are planktonic, that is, they drift with the ocean currents.

Shown: *Calanus marshallae*



Monthly anomalies of copepod species richness*

Source: NOAA, 2008

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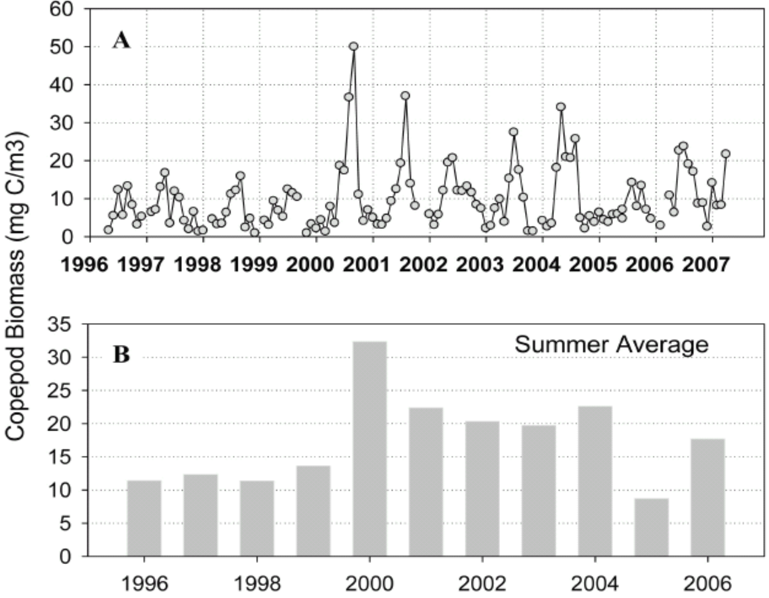
* Copepod species richness is the average number of copepod species in a sample of plankton. The anomaly is the difference between the monthly, and the long-term, average copepod species richness values.



Monthly averaged copepod biomass

Source: Goericke, et al., 2007

What is the indicator showing?

The indicator presents trends in copepod biodiversity, or species richness, off the coast of Newport, Oregon. The monitoring site is located about 300 kilometers north of Crescent City, California, in the northern portion of the California Current System. Copepods are carried in waters transported by the California Current from sub-Arctic regions, along the coast of Oregon, to the California coast (see page 72). Thus, changes in copepod populations at this site are indicative of changes occurring off the California coast.

The copepod species richness index represents the average number of copepod species in monthly plankton samples. The top graph presents monthly anomalies -- or departure from the long-term (i.e., from 1996 to 2005) monthly average -- in copepod species richness. Each value on the graph is derived by subtracting the observed average number of copepod species for a given month from the long-term average number of species for that month. Hence, values are negative when the observed number of copepod species is less than the long-term monthly average, and positive when the observed number is greater. Copepod species richness was low from 1999 until 2002, high from 2003 until the fall of 2006, and generally low since.

Negative values indicate that the copepods are being transported to Oregon chiefly from the north, out of the coastal subarctic Pacific, a region of low species diversity. Copepods from this cold-water region are referred to as northern species. Two of the northern species, *Calanus marshallae* and *Pseudocalanus mimus*, are lipid-rich, containing wax esters and fatty acids that appear to be essential for many pelagic fishes to grow and survive through the winter. Positive values indicate that the waters originate either from the south or from offshore, which are warm, low-salinity waters containing a more species-rich planktonic fauna, referred to as southern species. These southern copepod species are smaller than northern species, and have low lipid reserves.

Copepod biomass (the total weight of all copepods) varies seasonally, with peaks in July to August, and interannually (middle graph). The bottom graph shows that the highest averages for the summer (May to September) were seen for 2000 to 2004. Lowest summer averages occurred from 1996 to 1999, with the lowest biomass of any summer occurring in 2005. High copepod biomass is accompanied by low species richness (biodiversity), and vice versa, with changes following a seasonal pattern of low diversity in the summer and high diversity in the winter.

Why is this indicator important?

Copepods are the base of the food chain for most fishes (especially anchovies, sardines, herring, smelt and sand lance). Tracking copepods provides information about changes occurring in the food chain that fuels upper trophic level marine fishes, birds, and mammals. Knowledge of year-to-year variations in their abundance and species composition may predict the abundance of small fishes, as well as the salmon and other fish, marine mammals, and sea birds that feed on these fish. As noted above, “northern species” are larger and bioenergeticaly richer than the “southern species." When copepods largely consist of northern species, the pelagic (water column) ecosystem is far more productive than when southern species dominate.

It is noteworthy that the four years of negative anomalies of copepod species richness from 1999-2002 are correlated with extraordinarily high returns of Coho and Chinook salmon to the rivers of California and Oregon. In addition, the years 2003-2007, when salmon returns began to decline dramatically, are correlated with positive anomalies of copepod species. These observations indicate a rich food chain from 1999-2002, and an impoverished food chain from 2003-2007.

Like other zooplankton, copepods are useful in the study of ecosystem response to climate variability. Due to their short life cycles (on the order of weeks), their populations respond to, and reflect short-term and seasonal changes in environmental conditions. Moreover, many zooplankton taxa are indicator species whose presence or absence may represent the relative influence of different water types on ecosystem structure. Copepod species reflect ocean transport processes in the northern California Current. Anomalously low (i.e., negative) numbers of copepod species indicate the transport of coastal subarctic water into the coastal waters of the northern California Current (as in 1999-2002), while anomalously high numbers of species are associated with either a greater amount of onshore transport of warm, offshore, subtropic water, or northward transport of subtropical coastal water along the coastal corridor (as happened in late 2002 to early 2006).

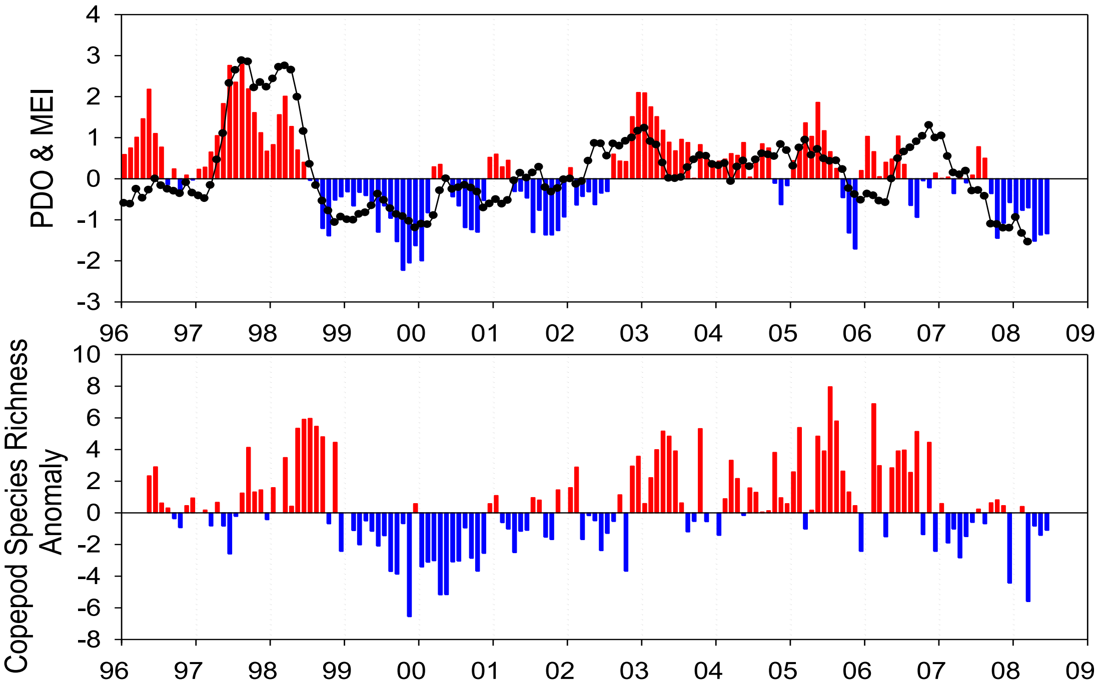
Finally, copepod populations may give a one-year advance warning of major changes in oceans conditions. Copepod indices have proven useful for the prediction of the returns of Coho salmon (Peterson and Schwing, 2003), and forecasts of salmon survival have been developed for the Washington/Oregon coasts based on certain indices (see http://www.nwfsc.noaa.gov/ and click on "Ocean Index Tool").

These same copepod indices have been correlated with: anchovy recruitment (the term "recruitment" means the addition of young to a population) (R. Emmett, personal communication); sablefish recruitment (M. Schirippa, personal communication); seabird nesting success in Central California (W. Sydeman, personal communication); and seabird mortality off northern Washington (J. Parrish, personal communication).

What factors influence this indicator?

Copepod dynamics in this region of the California Current display strong seasonal patterns, influenced by circulation patterns of coastal currents. The copepod community tends to be dominated by cold-water species during the upwelling season, typically from May through September, as winds blow toward the equator and subarctic waters are transported southward from the Gulf of Alaska. As noted above, the cold-water copepod species are characterized by low species diversity. During winter, offshore waters and warmer waters from the south carry more zooplankton species-rich water to the Oregon continental shelf.

The interannual patterns of species richness are found to track two measures of ocean climate variability -- the Pacific Decadal Oscillation (PDO) and the Multivariate El Niño Southern Oscillation Index (MEI). The PDO is a climate index based on ocean temperatures across the entire North Pacific Ocean. When the ocean is cold in the eastern Pacific, the PDO has a negative value; when the ocean is warm in the California Current, the PDO has a positive value. In addition to atmospheric conditions in the North Pacific Ocean (as indexed by the PDO), coastal waters off the Pacific Northwest are also influenced by equatorial Pacific atmospheric conditions, especially during El Niño events. The presence or absence of conditions resulting from the El Niño Southern Oscillation is gauged using the MEI. Positive MEI values indicate El Niño conditions at the equator (i.e., warming), while negative values indicate cooling in the eastern equatorial Pacific. These patterns are particularly striking when the PDO and MEI are of the same sign.



Source: NOAA, 2008

The graph above shows two time series of monthly values of the PDO (red and blue bars) and the MEI (black dots and lines). The lower panel is the same graph presented above of the monthly anomaly of the number of copepod species in plankton samples. There are clear relationships between interannual variability in the physical climate indicators (PDO and MEI) and copepod species richness anomalies.

While the copepod index predominantly describes interannual to decadal climate variability, it is likely to indicate long-term climate change, since changes in ocean transport and water mass source are responsive to variations in global climate. As this index grows over time, it may reveal a clear trend toward one dominant group of copepod species due to climate change.

Technical Considerations:

Data Characteristics

The copepod data are based on biweekly sampling off Newport, Oregon, and are usually available by the end of each month. The sampling station is a coastal shelf station located 9 kilometers offshore, at a water depth of 62 meters. Samples are generally collected during daylight hours, using nets hauled from 5 meters off the bottom to the surface. Zooplankton is enumerated by species and developmental stage, and taxa-specific biomass estimated from literature values or the investigators' unpublished data of carbon weights. Samples are generally processed by the same person, thereby limiting any potential taxonomic inconsistencies or bias among plankton counters.

Values are posted to a website, but the site is currently updated only every six months. However, monthly values are available to anyone who requests them. Details of our sampling program and data analysis can be seen in Peterson and Keister (2003), Peterson and Schwing (2003), and Hooff and Peterson (2006).

Strengths and Limitations of the Data

Although there are some historical data on copepod species, the present monitoring work is a time series of 13 years in length. Twenty years' worth of data may be required in order to perform rigorous statistical analyses to examine relationships between copepod populations and fish, birds, and mammals.

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For more information, contact:

Bill Peterson
NOAA Fisheries
Hatfield Marine Science Center
Newport, OR 97365
(541) 867-0201
Bill.peterson@noaa.gov

Impacts on biological systems: Animals

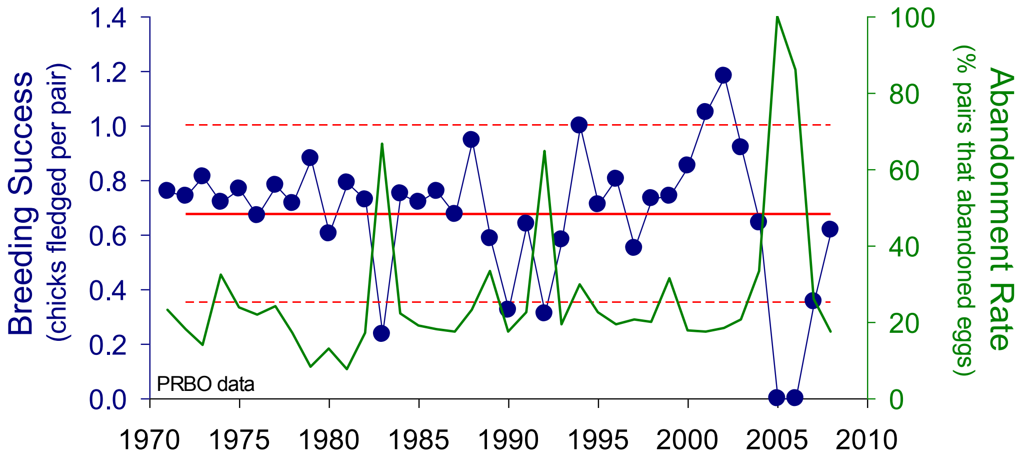
CASSIN'S AUKLET POPULATIONS

Auklet breeding success has become more variable through time, with unprecedented reproductive failures in 2005 and 2006.

Photo: Ron LeValley

The Cassin's Auklet (*Ptychoramphus aleuticus*) is a small, diving seabird. Its breeding range extends from the Aleutian Islands, Alaska to islands off middle Baja California peninsula. Its center of distribution is located off British Columbia, on Triangle Island (Rodway 1991). Important colonies in California occur on Southeast Farallon Island (part of the Farallon National Wildlife Refuge, located 26 miles west of San Francisco, California) and on the Channel Islands off southern California. These birds eat zooplankton, primarily calanoid copepods and euphausiids off British Columbia and "krill", inch-long shrimp-like crustaceans, on the Farallon and Channel islands to the south (Manuwal and Thoresen, 1993).

BREEDING SUCCESS OF AUKLETS ON THE FARALLON ISLANDS, CA*



* The solid red line shows the long-term mean breeding success (0.68 chicks per pair). Dashed red lines show +80 percent confidence intervals.

What is the indicator showing?

The graph shows breeding success, measured as the average number of offspring produced per year by each breeding pair of auklets in study sites (nest boxes and burrows) on Southeast Farallon Island. The same data are summarized by decade in the table below. A linear trend in the data was not apparent. However, both the graph and the table show that over the past four decades breeding success has become increasingly variable, with both the highest and lowest years on record happening in the present decade (Peterson et al., 2006; Sydeman et al., 2006; PRBO unpublished data).

Furthermore, although significant drops in breeding success occurred in 1983, 1990, and 1992, complete failure was not observed until 2005.

Breeding success by decade for the Cassin's Auklet,
on Southeast Farallon Island, California.

Decade	Mean Breeding Success	Coefficient of variation
1971-1980	0.745	10.2
1981-1990	0.652	33.2
1991-2000	0.693	27.1
2001-2008	0.597	75.7

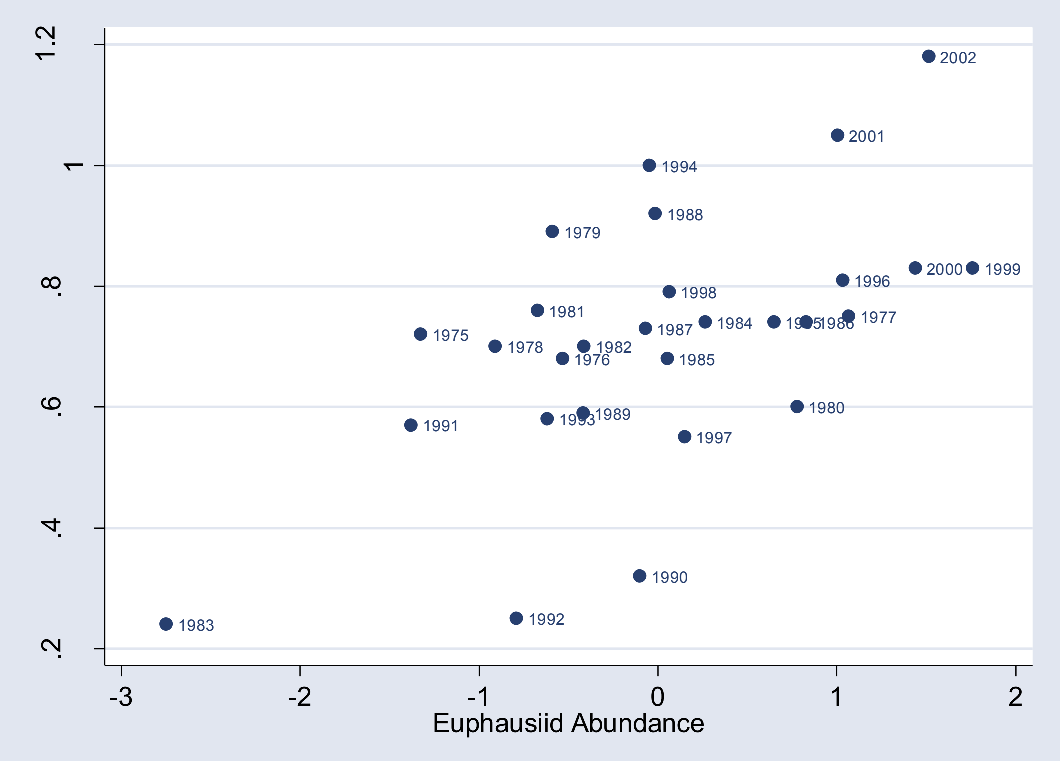
The graph also shows an "abandonment rate", which is calculated as the proportion of breeding pairs which permanently left eggs unattended during incubation. The abandonment rates during the El Niño events of 1983 and 1992 were markedly higher than in other years, with roughly 65 percent of the breeding pairs leaving the colony. In 2005 and 2006, unprecedented abandonment rates of 100 and 86 percent, respectively, were observed.

Why is this indicator important?

Seabirds such as the auklet respond to changes in prey availability and prey quality, which in turn are related to climate (Wolf et al., 2008). Hence, seabirds can be used as reliable "indicators" of food web changes in marine ecosystems (Piatt et al., 2007). Seabirds are the most conspicuous of all marine organisms, and changes in their populations or vital rates may reflect changes in species that make up their prey base, such as krill, which are more difficult to study (Piatt et al. 2007). Measurements of auklet breeding success and abandonment rates provide a strong signal of changes in prey availability in the ecosystem over the period of time when the birds are reproductively active each year (March through August).

Krill are the main prey consumed by auklet chicks on Southeast Farallon Island, accounting for about 80 percent of their diet in most years (Sydeman et al., 1997; Sydeman et al., 2001; Abraham and Sydeman, 2004). The auklet feeds primarily on two species -- *Euphausia pacifica* and *Thysanoessa spinifera* – as well as mysids (another zooplankton) and some larval fishes (sanddabs, rockfish, etc). Estimates of krill biomass in part of the auklet's foraging grounds in the Gulf of the Farallones in 2005 were about half of that found in 2004 (Jahncke et al., 2008). Estimates of krill biomass off northern California in the spring of 2005 also were lower than samples collected in the region between 1990 and 2005 (Sydeman et al., 2006). However, more recent analyses of acoustic data show more krill, in general, in the central-northern California region in 2005 than 2004, although they were distributed in smaller patches (JA Santora, WJ Sydeman and SR Ralston, unpublished data). In 2006, krill were largely absent throughout most of central-northern California region. In 2005 and 2006, limited food sampling showed that the auklets were feeding exclusively on mysids (PRBO, unpublished data), but too few samples were obtained to characterize diet composition.

Auklet breeding success is positively related to krill (or “euphausiid”) abundance. In the figure below, krill abundance, estimated from a model, explains 35 percent of the variation in breeding success (data from Abraham and Sydeman, 2004). This figure combines estimates of abundance for both species of krill that are known to be consumed by the auklets.



The reproductive failures observed on Southeast Farallon Island in 2005 and 2006 were accompanied by a marked increase in summer auklet abundance off southern California (i.e., south of Point Conception), and this unusual abundance was positively correlated with the abandonment rate (Sydeman et al., 2006). These observations are suggestive of auklet emigration from the north. Furthermore, biomass estimates were higher (for *Thysanoessa spinifera*), or the same as (for *Euphausia pacifica*), in the waters off southern California in the spring of 2005 when compared to earlier years (Sydeman et al., 2006).

The auklet breeding success indicator is important because it reflects bio- physical processes occurring in the marine ecosystem that are difficult to measure directly. The record from the seabirds suggests that ocean warming and other forms of “marine climate change” are affecting the coastal food web, particularly krill, a major food resource not only for seabirds, but also salmon, other fish, and mammals. Ocean warming (Levitus et al., 2001) may reduce the efficacy of upwelling – the upward movement of deep, cold, nutrient-rich waters to the surface, where plankton growth occurs. As a consequence, fewer nutrients are exposed to light, leading to a reduction in photosynthesis by phytoplankton and, ultimately, zooplankton such as krill. A study by Roemmich and McGowan (1995) has shown an 80% decrease in zooplankton biomass in the waters off southern California over a period of about 40 years (1951-1992), a trend which continues to this day. In addition, seabird breeding success has been shown to correlate with salmon abundance (Roth et al., 2007), indicating that the reduction of krill abundance may be affecting salmon as well.

What factors influence this indicator?

Cassin's auklet breeding success on Southeast Farallon Island is associated with various measurements of ocean climate (Abraham and Sydeman 2004; Sydeman et al., 2006; Jahncke et al. 2008; Wells et al., 2008). In addition to marine climate change, the El Niño-Southern Oscillation (ENSO) cycle imposes constraints on the upwelling process. El Niño / La Niña are responsible for warm (and cold) ocean temperatures, which can reduce or enhance ocean productivity by capping or intensifying aspects of upwelling. During a typical El Niño, the ocean warms 1-2 degrees Celsius (°C) above its climatological average (WRCC, 1998), often leading to a collapse of the food web.

Auklets may respond to moderate ocean warming by delaying egg laying to time hatching so chicks have a reliable food source (Abraham and Sydeman, 2004), but during two of the strongest El Niño conditions during the last three decades (1982-83, 1991-1992), the auklets could not adapt and there was a substantial decrease in auklet breeding success. The years 2005 and 2006 were not, however, characterized as El Niño.

Technical Considerations:

Data Characteristics

Breeding success of Cassin's Auklets is measured by monitoring breeding birds in 44 nest boxes on Southeast Farallon Island (Abraham and Sydeman, 2004; Lee et al., 2007). Approximately 80 percent of the boxes are occupied by breeding birds each year, although fewer pairs attempt reproduction in years of poor food availability. Each nest box is checked every 5 days for nesting activity. Parental birds are banded for future identification. The date of egg-laying, number of eggs laid and hatched, and the number of chicks raised to independence by each breeding pair is counted. For this indicator, the overall annual breeding success is assessed as the average number of offspring fledged per breeding pair per year.

Strengths and Limitations of the Data

Long records of seabird breeding success are uncommon. The record of auklet breeding success at Southeast Farallon Island has been collected and maintained by PRBO Conservation Science (formerly Point Reyes Bird Observatory) under a long-term contract with the U.S. Fish and Wildlife Service since the early 1970s. This is the longest continuous record of its kind on the U.S. west coast, and is one of the most extensive in the world.

The west coast marine ecosystem is affected by strong interannual (exemplified by El Niño/La Niña) and multi-decadal (Pacific Decadal Oscillation; Mantua et al. 1997) variability in temperature. Natural fluctuations in temperature and other physical factors make it difficult to isolate the magnitude of the anthropogenic climate change signal in this indicator.

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For more information, contact:

William J. Sydeman, PhD
President and Senior Scientist
Farallon Institute for Advanced Ecosystem Research
PO Box 750756
Petaluma, CA 94975
wsydeman@comcast.net
(707) 478-1381

Jaime Jahncke, PhD
Marine Ecology Director
PRBO Conservation Science
3820 Cypress Drive, No. 11
Petaluma, CA 94954
jjahncke@prbo.org
(707) 781-2555 x335

Russell W. Bradley
Farallon Program Manager
PRBO Conservation Science
3820 Cypress Drive, No. 11
Petaluma, CA 94954
rbradley@prbo.org
(707) 781-2555 x314

APPENDIX A.

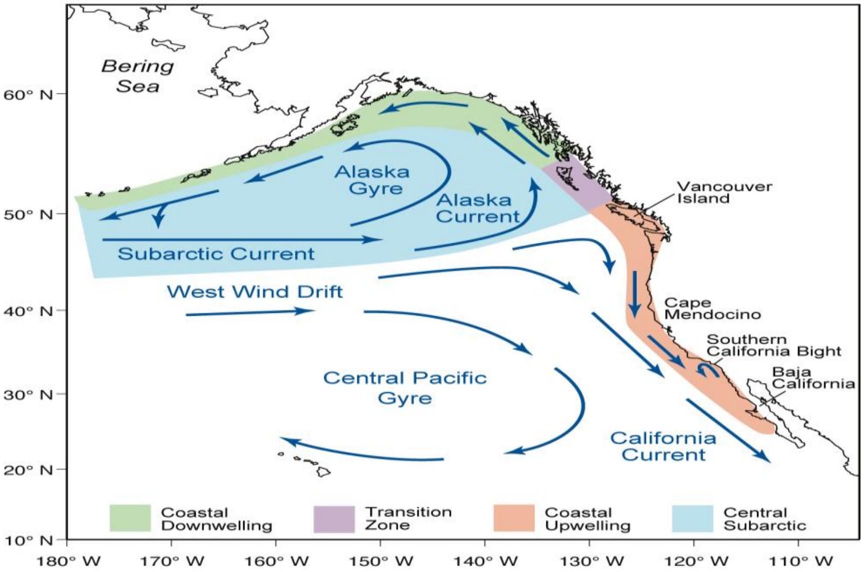
NORTH PACIFIC OCEAN CONDITIONS AND PROJECTIONS FOR CLIMATE CHANGE

Contributed by:
Franklin Schwing
Southwest Fisheries Science Center/Environmental Research Division
National Oceanic and Atmospheric Administration

The Pacific Ocean influences California's mild, Mediterranean climate. Temperature and precipitation patterns for much of the state, including the cool wet winters and warm dry summers flavored with coastal fog, are determined largely by ocean conditions. Even the weather in the Sierras and over much of the nation is influenced by conditions in the North Pacific Ocean.

The broad southward-flowing ocean current that is part of the clockwise circulation vortex pattern of the North Pacific (gyre) is known as the California Current (Figure 1). This coastal current transports relatively cool, fresh (low salinity), and nutrient-rich water, as well as many organisms, from sub-Arctic regions to the California coast. This sub-Arctic water also contains a different composition of plant and animal species than the more sub-tropical, oceanic water over which it flows. A regional process known as "upwelling" carries the deep, cooler waters transported by the current upward, closer to the surface where photosynthesis by phytoplankton occurs (Smith, 1968; Huyer, 1983). The biologically productive coastal region, dominated by valuable fisheries such as sardine, market squid and salmon, and a variety of marine mammals, turtles, and birds, is one consequence of this nutrient-rich current (Parrish et al., 1981).

Figure 1. California Current

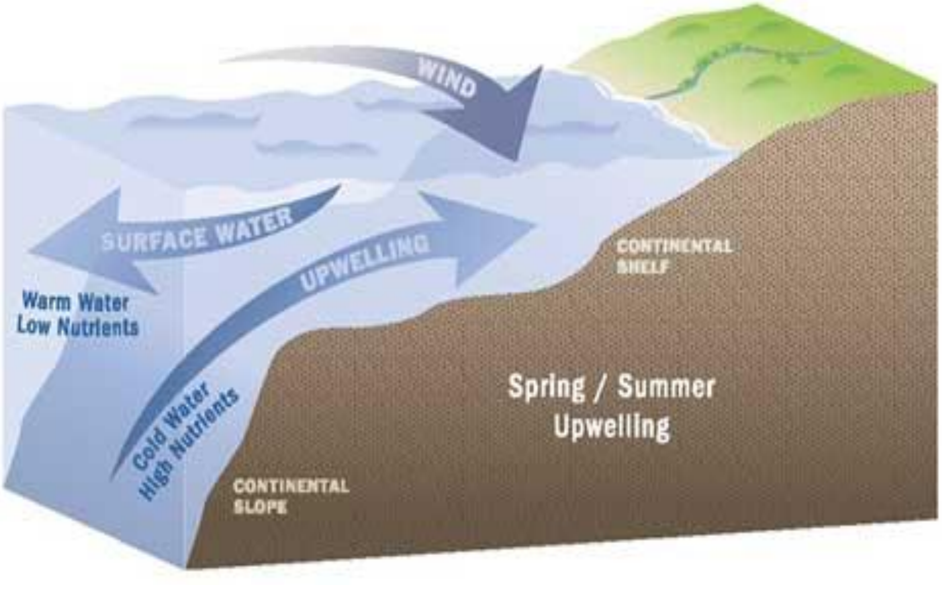


Source: J.A. Barth, Oregon State University, 2007

Prevailing winds over the North Pacific drive both the California Current and upwelling, on different space and time scales. Ocean circulation for the North Pacific basin is caused by large-scale winds, combined with the Earth's rotation. The North Pacific gyre adjusts to changes in global climate by transfers in heat and momentum of wind forces, on scales of months to years. Since the principal characteristics of the California Current ecosystem are linked so strongly to a small set of atmospheric processes, it is no surprise that variations in the intensity and timing of winds are often connected to global-scale shifts, which can cause significant changes in ecosystem production and organization.

Coastal upwelling is due to the onset of local coastal winds from the northwest. These winds are associated with the atmospheric high-pressure system that strengthens in spring and summer, the upwelling "season" [Figure 2]. The strong northwest winds (roughly parallel to the coastline) `drive surface waters away from the coast, replacing these with the upwelling of deeper cooler waters. As air flows offshore from land over the cooler upwelled waters, its moisture condenses into fog. Unlike the relatively slow adjustment of the North Pacific gyre, upwelling responds within a day to fluctuations in coastal winds (Rosenfeld et al., 1994) and can intensify and relax as the alongshore wind strengthens and weakens. Similar upwelling-dominated ecosystems are found off the west coast of South America, Africa, and Iberia.

Figure 2. Upwelling near the California Coast



Source: National Oceanic and Atmospheric Administration,
Cordell Bank National Marine Sanctuary, 2007

Changes in the flow of the California Current affect local water quality, including the biological effectiveness of upwelling. Greater transport of nutrient-rich water from the north means that upwelled water will support more biological productivity in surface waters. As California Current transport decreases due to changing climate conditions, coastal water will include relatively more subtropical water, and the upwelling of this water will lead to less primary production.

Another consequence of lower transport by the California Current is lower oxygen in coastal areas (Bograd et al. 2008), since subtropical water carries less dissolved oxygen (Stramma et al., 2008). During reduced southward flow, a shallow oxygen-deficient zone can develop, which reduces the depth of favorable habitat for many marine organisms.

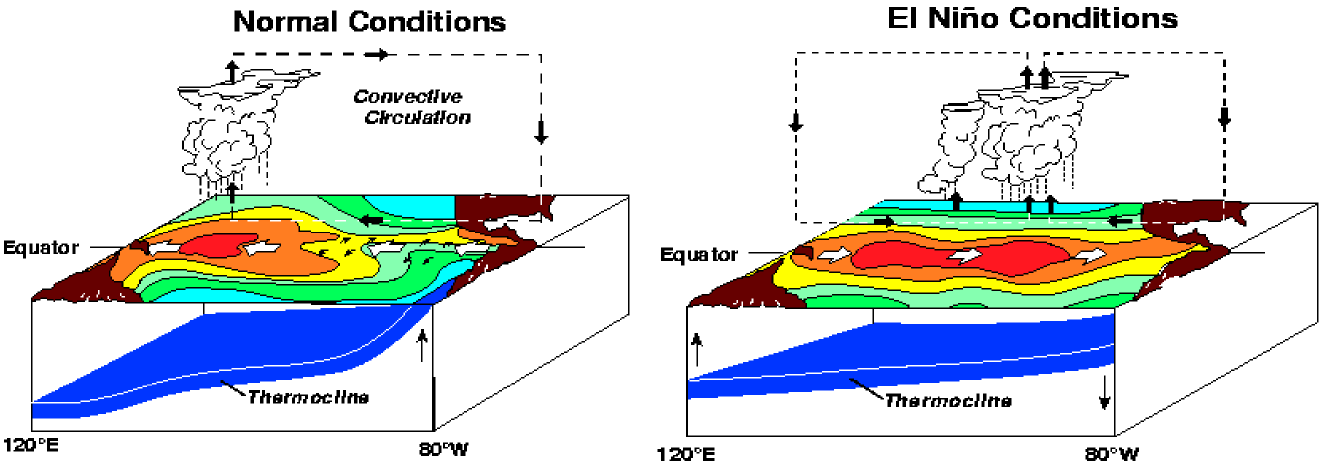
Another factor that influences upwelling is vertical stratification, which is a measure of the increase in water density with depth. Higher stratification represents a greater contrast between the less dense (warmer, fresher) surface water layer and denser (cooler, more saline) deep water; greater wind energy is required to mix these layers or to upwell nutrients to the surface. Thus, a consequence of global warming will be a more strongly stratified coastal ocean and less biological productivity (Roemmich and McGowan, 1995).

Variability in climate, with characteristic patterns in space and cycles or oscillations in time, is increasingly recognized to be part of a global interconnected system. The timing, evolution and signals of these patterns influence our weather (e.g., heatwaves, fog, snowpack, floods, droughts), one of the more obvious aspects of our environment. Likewise, global climate change will drive this ecosystem into a new, possibly previously unknown state. The California Current ecosystem is also impacted heavily by climate change. The dominant climate variability affecting California is identified by a few important climate phenomena and indices, including the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO).

El Niño-Southern Oscillation

El Niño (Philander, 1990) is the ocean part of a climate disruption of global oceanic and atmospheric conditions that originates from the tropical Pacific [Figure 3]. It often produces heavy rains and floods in California, droughts and wildfires in Australia, and fewer Atlantic hurricanes. One of the factors that cause El Niño events is the Southern Oscillation (SO), a fluctuation in atmospheric air pressure at sea level between the western and central tropical Pacific. During the positive phase of ENSO (El Niño), abnormally high atmospheric pressures develop in the western tropical Pacific and Indian Ocean regions, and unusually low pressure develops in the southeastern tropical Pacific. This is associated with a large-scale weakening of the Pacific trade winds, leading to warming of the surface waters in the eastern and central equatorial Pacific Ocean.

Figure 3. Schematic of the tropical Pacific, showing atmospheric circulation, sea surface temperature anomalies, and position of thermocline



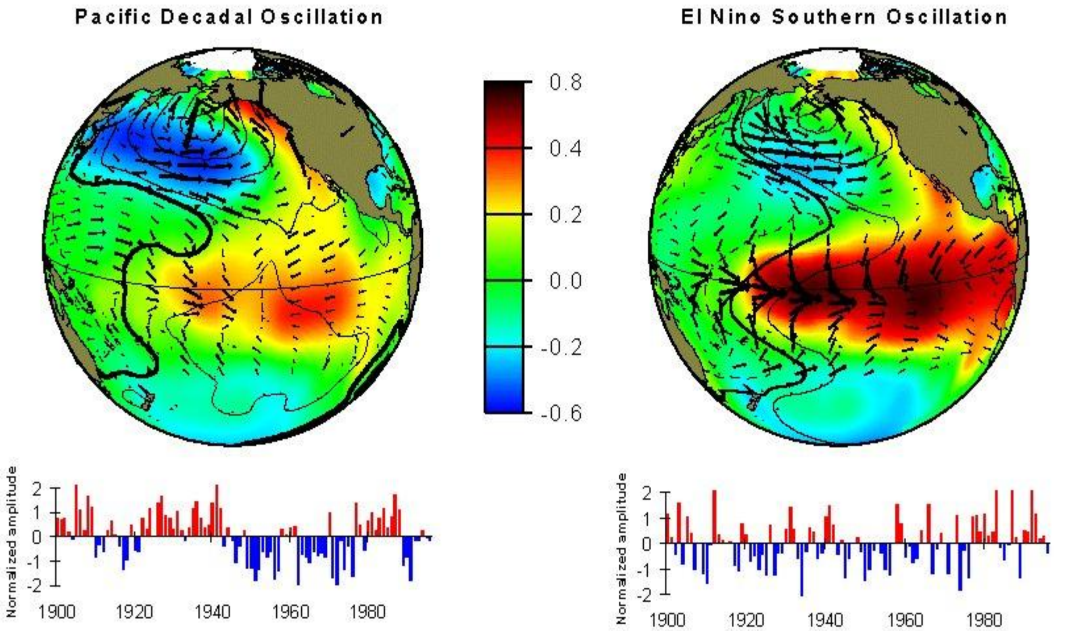
El Niño events occur irregularly at intervals of two to seven years, with the strongest events occurring about once per decade (1941-42, 1957-58, 1965-66, 1972-73, 1982-83, 1986-87, 1997-98). They typically last 12 to18 months, peaking along the coasts of North and South America around December (hence the name El Niño, Spanish for The Child, in reference to Christmas). The negative phase of ENSO, called La Niña, occurs when the trade winds blow unusually hard and the ocean temperatures become colder than normal.

Along the west coast of the U.S., as well as South America, El Niño events often reduce upwelling, which means warmer waters and fewer nutrients in surface waters. This temporarily lowers ecosystem growth and can be responsible for the temporary collapse of important commercial fisheries in addition to marine mammal and sea bird populations. Because this is a long-established natural cycle, the ecosystem eventually recovers. The signal of El Niño can be seen in the four ocean climate indicators: warmer temperature, lower oxygen, higher copepod species richness, and poorer sea bird breeding success. However, not every El Niño event is identical; the timing, strength, and regions of greatest impact vary with event (Mendelssohn et al., 2003).

Pacific Decadal Oscillation

The Pacific Decadal Oscillation represents a much longer-scale (multi-decadal) phenomenon [Figure 4]. The PDO is based on a statistical analysis of ocean observations, and is the first principle component of monthly ocean surface temperature patterns for the North Pacific (Mantua et al., 1997). Typically, the phases of the PDO, referred to as regimes, represent relatively stable ocean states, separated by sharp and rapid transitions, called regime shifts. Warm (so-called because ocean temperatures along the coast of North America are unusually warm, but cool in the central North Pacific) PDO regimes dominated in 1925-1946 and from 1977 into the late1990s. Cool PDO regimes prevailed from 1890-1924 and from 1947-1976, and there is some suggestion that the PDO returned to its cool phase in 1998. It must be noted that the PDO is an indicator of multi-decadal climate variability in ocean temperature, not a climate process like ENSO that has a clear physical mechanism. Scientists are working to understand the mechanisms responsible for the natural decadal variability represented by the PDO. Understanding these variations will improve our ability to detect and quantify anthropogenic changes.

Figure 4. Typical wintertime sea surface temperature (colors), sea level pressure (contours) and surface wind stress (arrows) anomaly patterns during the positive (warm) PDO (left) and positive (El Nino) ENSO phases



Source: N.J. Mantua, University of Washington, 1997

The positive phase of the PDO is associated with warmer than normal ocean temperatures off California and generally lower biological productivity, as seen in the ocean indicators. Different dominant assemblages of fish and marine species characterize the phases of the PDO (Peterson and Schwing, 2003). For example, sardine is typically the dominant fishery during the positive (warm) PDO phase, while anchovy and salmon thrive in its cool phase.

The PDO appears to have considerable influence on terrestrial systems as well. Warm phases of the PDO are correlated with North American temperature and precipitation anomalies similar to El Niño, including warm and wet conditions for most of California, and increases in the volume of Sierra snowpack and flood frequency (Cayan, 1996). Over the western U.S., it also corresponds with periods of reduced forest growth {Peterson and Peterson, 2001), more extensive wildfires (Mote et al., 1999), and disease outbreaks. These anomalous conditions are more apparent when the positive PDO phase corresponds with El Niño.

California's Coastal Ocean and Climate Change Projections

Based on model climate projections from the Intergovernmental Panel on Climate Change (IPCC) and other sources, the likely consequences of future climate change to California's coastal ocean can be predicted. IPCC (2007) identifies a number of very likely (90-99% probability) changes in the 21st century of concern to coastal California. Some of the predicted ecological responses are already being noted, and could be a result of recent climate change.

Air and ocean temperatures are projected to become warmer, especially in summer, contributing to greater ocean stratification and weaker upwelling. The biological impact of this may be a lower rate of productivity and less food for many species, a northward shift in the distribution of many populations, and the expansion of invasive and exotic species in number and abundance, possibly outcompeting and displacing native species.

Changes in storm patterns and precipitation are likely to cause warmer and wetter winters; greater freshwater discharge into the coastal ocean, and coastal flooding. Projected shifts in precipitation and Sierra snowmelt will modify the seasonal patterns of streamflow. These changes could reduce coastal water quality, and increase toxic algal blooms and other ocean-borne health hazards. Changes in freshwater flow, as well as stream temperatures, would be particularly critical to salmon and other anadramous stocks. Higher coastal sea level could displace intertidal species and reduce the area of coastal and estuarine wetlands that are crucial nursery grounds for many marine species.

Other likely (66-90% probability) 21st century changes have been identified (IPCC, 2007). More extreme weather and climate events, such as stronger storms and greater coastal erosion, more frequent or intense El Niño events, and perhaps even hurricanes are possible. Important fisheries could be displaced and reduced during such events, but exotic subtropical fisheries may become available. Alterations in the winds may change the North Pacific gyre circulation patterns which will affect the transport of nutrients, dissolved oxygen, and marine organisms. Increased CO_2 concentrations in the upper ocean will lower pH and cause the water to become more acidic to marine life (Feely et al., 2004). The impacts of this are just being explored, but could include a substantial disruption of the food chain in the California Current. Changing seasonal cycles are also likely (Parmesan and Yohe, 2003). One likely scenario is a delay in the start of the upwelling season and, consequently, a delay of the spring plankton bloom (Snyder et al., 2003). This will impact migration and reproductive cycles of fish, birds and marine animals as their source of food is not synchronized with their life cycles (Mackas et al., 2006; Sydeman et al., 2006).

While indicators (e.g., Scripps ocean temperature) with long-term tendencies such as warming throughout the 20th century suggest trends due to increased greenhouse gases and anthropogenic climate change, indicators featuring multi-year climate variability are equally important in characterizing climate change. One of the limitations to quantifying and projecting climate change is distinguishing between natural and anthropogenic signals in many observational records. Indicators with interannual to interdecadal variability associated with natural phenomena like ENSO and the PDO are necessary to isolate anthropogenic signals.

These natural variations also help us to understand the relationships between climate forcing and their impacts on human systems and ecosystems. They help identify the key physical drivers of natural climate variability and ecosystem response. This insight is vital to improve the ability to predict how future climate change will shape California and our world.

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For more information contact:
Office of Environmental Health Hazard Assessment
P.O. Box 4010, Mail Stop 12-B
Sacramento, CA 95812-4010
(916)324-2829

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