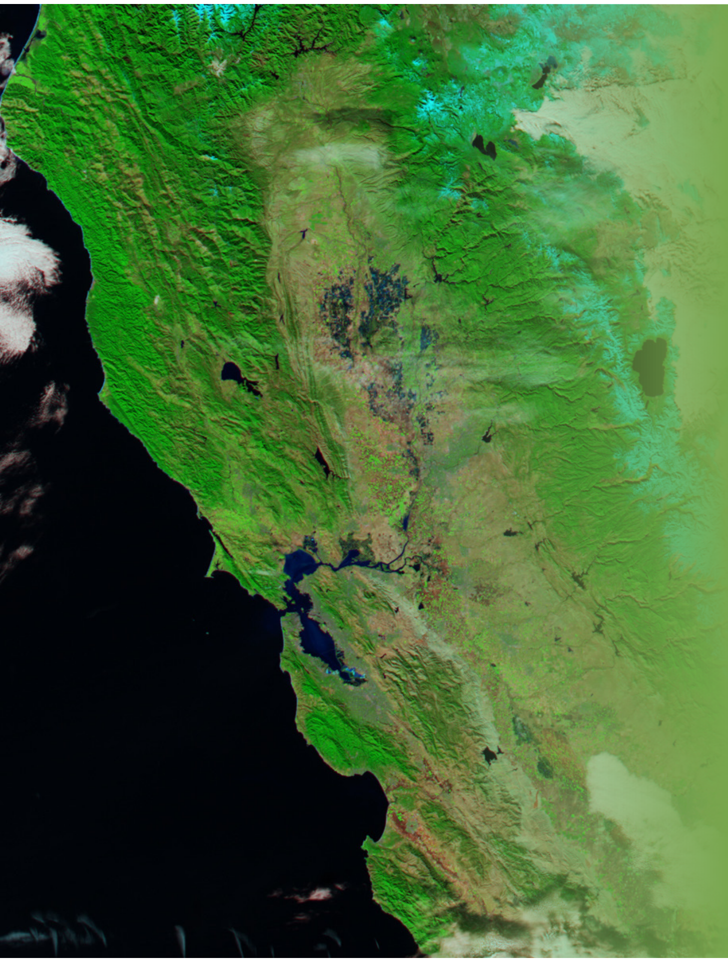
August 2013



Indicators of Climate Change in California

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INDICATORS OF CLIMATE CHANGE IN CALIFORNIA

August 2013

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ACKNOWLEDGEMENT:
OEHHA is grateful to the Cal/EPA Office of the Secretary,
and to the staff and researchers (listed on the next page)
who contributed their ideas, data, findings and other information
for inclusion in this report.

Cover design: California Air Resources Board

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PREFACE

Indicators of Climate Change in California characterizes the multiple facets of climate change in California. The report tracks trends in greenhouse gas levels that influence climate, changes in the state's climate, and the impacts of climate change on California's environment and people.

The report does this by bringing together and displaying large amounts of scientific data as "indicators". These indicators rely on monitoring and research activities carried out by state and federal agencies, universities, and other research institutions. The indicators selected reflect current understanding about the role of heat-trapping greenhouse gases in climate change, how temperature and precipitation are changing, and how these changes are affecting the environment, specifically freshwater and marine systems, as well as humans, plants and animals. This 2013 edition updates a report published in 2009.

California has played a pioneering role as a leader in climate policy, planning and research. The indicators can help the state track, assess, and report on the climate change issues it is working to address. They facilitate communication of complex information to a broad audience in a relatively simple, systematic manner. Finally, by compiling indicators representing the many aspects of climate change in a single document, this report can serve as a valuable resource for decision-makers, scientists, educators, and other interested individuals.

This compilation of indicators will be updated periodically. In addition to having updated information from existing indicators, future reports may have new indicators and may modify or delete existing indicators, as warranted by new scientific information. Cal/EPA welcomes input from the research community, governmental agencies, non-governmental organizations, and other interested stakeholders. It is Cal/EPA's goal that the indicators, both individually and collectively, address the key aspects of climate change and promote informed dialogue about the state's efforts to monitor, mitigate, and prepare for climate change and its impacts.

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EXECUTIVE SUMMARY

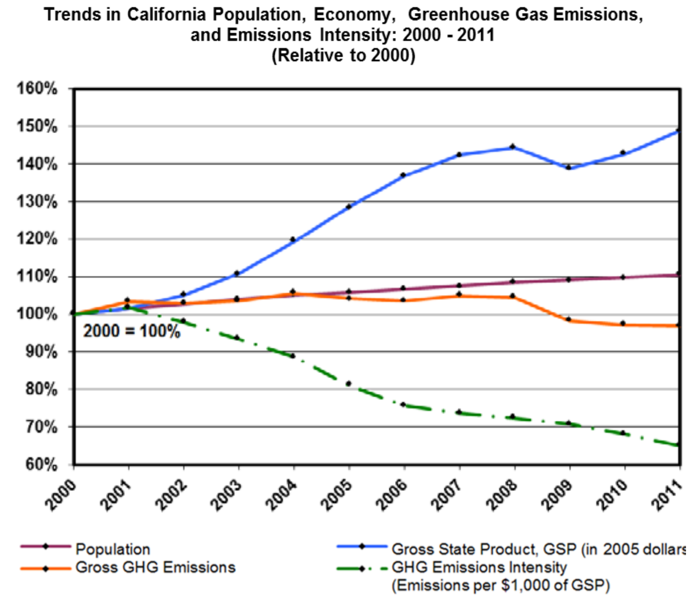
Scientists, policymakers and the people of California are concerned about climate-related impacts on the state's environment, public health and economy. This report compiles indicators that convey scientifically-based information on the status of, and trends in, California's climate and their impacts.

California has played a pioneering and a leadership role in climate policy, planning and research. The indicators of climate change can help the state in tracking, evaluating and reporting on the climate change issues it is working to address, as well as the outcomes of its efforts. The indicators serve as tools for communicating technical data in relatively simple terms. Taken collectively, the indicators help portray the interrelationships among climate and other physical and biological elements of the environment. Finally, many of the indicators reveal evidence of the already discernible impacts of climate change, highlighting the urgency for the state, local government and others to undertake mitigation and adaptation strategies.

> **Climate change** refers to "a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer." (International Panel on Climate Change, 2007a)

CLIMATE CHANGE DRIVERS

Climate is affected by human factors (such as changes in land cover and emissions of certain pollutants), natural factors (such as solar radiation and volcanic eruptions), and its own internal dynamics. Indicators are presented for greenhouse gases (GHG) and aerosols, which enhance the heat-trapping capacity of the Earth's atmosphere.



Source: ARB, 2013

- ***Greenhouse gas emissions*** California emissions of greenhouse gases, namely carbon dioxide, methane, nitrous oxide, and high global warming potential gases have seen an overall increase between 1990 and 2011. In recent years, however, emissions have generally been declining. Emissions per $1,000 of the state's economic output (measured as gross state product, or GSP) have decreased from 2000 through 2011, despite increases in GSP and in the state’s population. Carbon dioxide from the combustion of fossil fuels for transportation accounts for the largest proportion of emissions.

- ***Atmospheric greenhouse gas concentrations***
  Atmospheric concentrations of the greenhouse gases carbon dioxide and methane have been increasing in coastal areas of the state. This is consistent with global trends, as represented by levels measured at Mauna Loa, Hawaii. Carbon dioxide levels at Mauna Loa rose from 315.7 parts per million (ppm) in 1958 to 389.7 ppm in 2010. Levels tend to be higher in California; for example, carbon dioxide values were between 392.7 to 398.3 ppm in 2010.

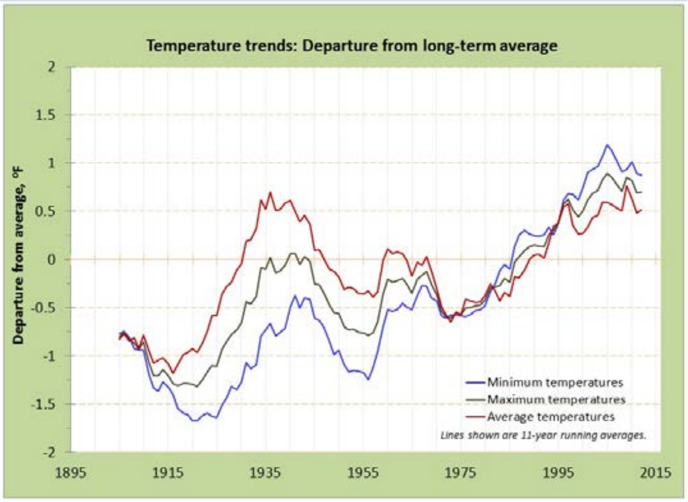
- ***Atmospheric black carbon concentrations***
  Atmospheric concentrations of black carbon, a powerful short-lived climate pollutant, have dropped significantly over the past several decades. A component of soot, black carbon is emitted by diesel-burning vehicles, residential wood burning and wildfires. Reductions in black carbon levels since the 1980s are due largely to reduced diesel engine emissions attributable to state air quality programs. Because black carbon is removed from the atmosphere in about a week, reducing its emissions represents an effective short term strategy to reduce climate warming.

- ***Acidification of coastal waters***
  The ocean absorbs nearly one-quarter of the carbon dioxide released into the atmosphere by human activities each year. As atmospheric levels of carbon dioxide increase, so do levels in the ocean, changing the chemistry of seawater. The coastal waters at Monterey Bay have increased in acidity since 1993 at a rate greater than in the open ocean near Hawaii.

CHANGES IN CLIMATE

Climate is generally defined as “average weather”. It is usually described in terms of the mean and variability of temperature, precipitation and wind over a period of time. Global observations of temperature increases and changes in other climate variables provide unequivocal evidence that the climate is warming. Climate scientists have shown that a large portion of the warming is human-influenced.

- ***Annual air temperature***
  Since 1895, annual average air temperatures in California have increased by about 1.5 degrees Fahrenheit (^{o}F), with minimum temperatures increasing at a rate almost twice as fast as the increase in maximum temperatures (approximately 2^{o}F/100 years and 1^{o}F/100 years, respectively). In most regions of the state, warming accelerated over the past three decades.



WRCC, 2013

- ***Extreme heat events***
  During the summer, heat extremes—measured as the intensity, frequency, duration and regional extent of heat patterns—have increased since 1950, especially at night. Nighttime heat waves have been increasing in all regions of the state. The Coastal North and Mojave regions have experienced the greatest increase in daytime heat waves.

- ***Winter chill***
  Warming is evident in other indicators. In the fruit growing valleys of California, winter chill time, a factor critical for fruit trees to produce flowers and fruit, has been decreasing since 1950.

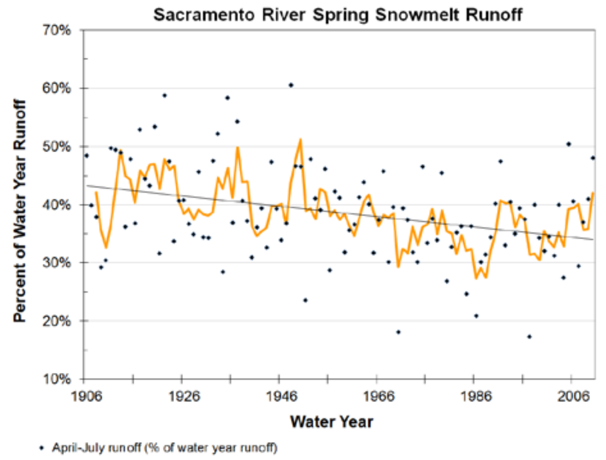
- ***Freezing level elevation***
  At Lake Tahoe, freezing level elevation—the altitude in the atmosphere at which temperatures drop below freezing—has risen by about 150 meters (500 feet) over the past twenty years, indicating warmer conditions at higher elevations.

- ***Precipitation***
  Large year-to-year variability in the amount of annual precipitation and periods of consecutive dry or wet years are evident, with no apparent trend.

IMPACTS ON PHYSICAL SYSTEMS

Climate is a key factor affecting snow, ice and frozen ground, streams, rivers, lakes and the ocean. Regional climate change, particularly warming temperatures, has affected these natural physical systems.

- ***Annual Sierra Nevada snowmelt runoff***
  Spring snowmelt from the Sierra Nevada to the Sacramento River has declined over the past century. Lower water volumes of snowmelt runoff indicate warmer winter temperatures. More precipitation falls as rain instead of snow and directly flows from watersheds before the spring. As a result, the portion of runoff that occurs between April and June has declined by about 9 percent. In addition to its impacts on the state’s water supply, reduced spring runoff can have adverse ecological impacts.



Source: DWR, 2011

- ***Snow-water content***
  While no overall trend is discernible in statewide snow-water content (the amount of water stored in snowpack), a decreasing trend has been observed in the northern Sierra Nevada, and an increasing trend in the southern Sierra Nevada. An integral part of California’s water supply, snowpacks store water that is later available to runoff or percolate into soils in spring and summer.

- ***Glacier change***
  Glaciers in the Sierra Nevada have decreased in area over the past century, consistent with a worldwide trend in response to a warming climate. A study of seven glaciers found their areal extent in 2004 to range from 22 to 69 percent of their area in 1900. Glacier shrinkage results in earlier peak water runoff and drier summer conditions, and worldwide is an important contributor to global sea level rise.

- ***Sea level rise***
  Sea levels measured at stations in San Francisco and La Jolla have risen at a rate of 8 and 6 inches over the century, respectively. Sea level rise in California could lead to flooding of low–lying areas, loss of coastal wetlands such as portions of the San Francisco Bay Delta system, erosion of cliffs and beaches, saltwater contamination of drinking water, impacts on roads and bridges and harmful ecological effects along the coastline.

- ***Lake water temperature***
  Average water temperatures in Lake Tahoe have risen by nearly 1°F in the past 30 years. Warmer waters in Lake Tahoe may be responsible for reduced lake clarity and making conditions favorable for certain algae and introduced species. Temperature data derived from satellite observations also show a significant warming trend since 1992 for summer nighttime temperatures at six lakes in California and Nevada, including Lake Tahoe.

- ***Coastal ocean temperature***
  Sea surface temperatures at La Jolla have increased by about 1.8^{o}F over the past century at about twice the global rate. Warmer ocean waters contribute to global sea level rise and extreme weather events, and can impact the marine ecosystem and its populations.

IMPACTS ON BIOLOGICAL SYSTEMS

Terrestrial, marine and freshwater biological systems are strongly influenced by climate, particularly warming. Plants and animals reproduce, grow and survive within specific habitat ranges defined by climatic and environmental conditions. Changes in these conditions may threaten the ability of species to survive or thrive.

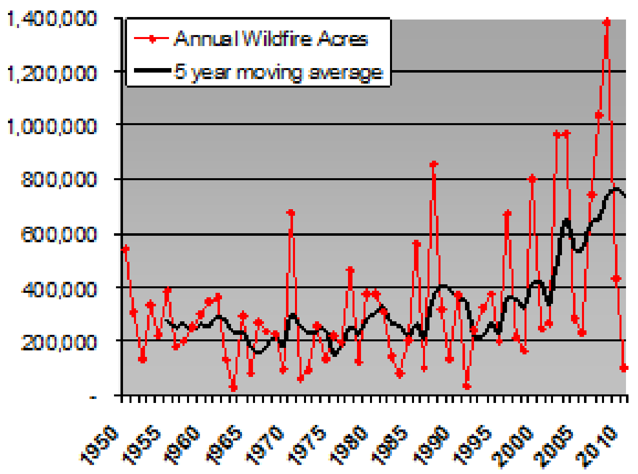
Shifts in the habitat elevation or latitude, changes in the timing of growth stages, changes in abundance and community composition, and increased vulnerability to wildfires or pathogens are examples of biological responses that have been influenced by warming temperatures.

- ***Heat-related mortality and morbidity***
  Although largely preventable, heat-related illnesses and deaths in humans are expected to result from continued warming and more frequent and intense heat waves. The July 2006 heat wave, unprecedented in its magnitude and geographic extent, resulted in 140 heat-related deaths in California.

- ***Tree mortality***
  Tree deaths in the Sierra Nevada and southern Cascade Mountains have increased with rising temperatures and water deficit (a measure of drought which integrates temperature and precipitation). Rapidly increasing tree mortality rates have also been found in unmanaged old forests across the western United States.

- ***Large wildfires***
  Since 1950, annual acreage burned in wildfires statewide has been increasing in California. The three largest fire years occurred in the last ten years. A large spike in annual average acreage of conifer and shrubland burned statewide occurred from 2000-2008. In the western United States, large wildfires have become more frequent, increasing in tandem with rising spring and summer temperatures.

Annual area burned by wildfires in California



Source: CalFire, 2011

- ***Forest vegetation patterns***
  The lower edge of the conifer-dominated forests in the Sierra Nevada has been retreating upslope over the past 60 years. These regions are experiencing a warming of winter nights, causing a shift in vegetation from needle-leafed to broad-leafed trees. This vegetation shift will impact birds, mammals and other species that rely on certain tree types for food and habitat.

- ***Subalpine forest density***
  Today's subalpine forests in the Sierra Nevada are much denser—that is, comprised of more small-diameter trees—than they were over 70 years ago. Small trees have increased by 62 percent, while large trees have decreased by 21 percent, resulting in 30 percent more stems today. During this time period, warmer temperatures, earlier snowmelt and more rain than snow occurred in this region. Densification of forests could lead to larger and more frequent fires and make trees more vulnerable to insect outbreaks and disease.

- ***Vegetation distribution shifts***
  In Southern California, the distribution of dominant plant species across a slope in the Santa Rosa Mountains has moved upward in the past 30 years by an average of 65 meters (213 feet). The climate of the canyon has become warmer and drier during this time period, suggesting that these conditions have been stressing the lower elevation plants and providing more favorable conditions for plants at higher elevations.

- ***Spring flight of Central Valley butterflies***
  Butterflies in the Central Valley have been appearing earlier in the spring over the past four decades, a change correlated with hotter and drier conditions in the region. This indicator complements studies from Europe that demonstrate a similar life cycle timing response of spring butterflies to warming and drying.

- ***Small mammal range shifts***
  Small mammals in Yosemite National Park are found today at different elevation ranges compared to earlier in the century. Most of these changes involved movement to higher elevations. Range contractions are of particular concern, given the decreased habitat area at higher elevations.

- Ocean conditions—including currents, winds and temperature—strongly influence marine populations. Spring and summer "upwelling" of cool nutrient-rich water supports tremendous biological productivity, supporting the marine food web. Warming temperatures and reduced upwelling can negatively affect the availability of food, in turn resulting in impacts on:

  - ***Sacramento fall run Chinook salmon abundance***
    Although fall run Chinook salmon abundance fluctuates year to year, it has declined dramatically since 2004 in the Central California region. Population abundance is related to prey availability in the ocean feeding grounds where juveniles feed before returning to spawn in fresh water.

- ***Cassin's auklet populations***
  Auklet breeding success on the Southeast Farallon Islands off the California coast has been more variable, with unprecedented reproductive failures in 2005 and 2006 and record high productivity in 2010. Auklet breeding success is positively related to prey abundance in adult foraging grounds.

- ***Shearwater and auklet populations off Southern California***
  Sooty Shearwater and Cassin's Auklet populations at sea in the Southern California Bight have declined significantly over the past 24 years. Changes in these populations may be related to ocean warming and changes in the distribution and abundance of prey.

- ***Sea lion pup mortality and coastal strandings***
  Increased California sea lion pup mortality and stranding of yearling pups is associated with irregular ocean conditions. Warmer sea surface temperatures reduces prey in the foraging zone and causes lactating females and newly weaned pups to travel farther offshore to obtain food. Lengthy foraging trips can leave nursing pups and newly weaned pups vulnerable to starvation.

EMERGING CLIMATE CHANGE ISSUES

Possible climate-related changes and impacts that are plausibly—but not yet established to be—influenced by climate change are referred to in this report as emerging issues. Scientifically defensible hypotheses, models and/or limited data support the assertion that certain observed or anticipated changes are in part due to climate change. These emerging issues may, in the future, be tracked as indicators of climate change once sufficient data on the influence of climate change become available. Examples include:

- An increase in the frequency, severity and duration of harmful algal blooms in all aquatic environments, which are known to be influenced by water temperature.

- Reduced duration and extent of winter fog in the Central Valley, with warming winter temperatures.

- Increased survival and spread of forest disease-causing pathogens and insects, along with increased susceptibility of trees, which are affected by temperature, precipitation or forest fires.

Source: DWR

- In addition to heat waves and wildfires, changes in the frequency and intensity of extreme events such as droughts and floods.

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INTRODUCTION

California has played a pioneering role as a leader in climate policy, planning and research. The state has a comprehensive strategy to mitigate climate change through greenhouse gas emissions reductions and to adapt to climate change by enhancing community resilience and infrastructure changes (see Appendix A). Climate change indicators can help the state track, evaluate and report on the climate change issues it is working to address, as well as the outcomes of its efforts. Taken collectively, indicators portray the interrelationships among climate and other physical and biological elements of the environment.

This report presents a collection of indicators of climate change in California. It updates and adds to indicators in the 2009 report, *Indicators of Climate Change in California*[1]*.* Many of the indicators reveal evidence of the already discernible impacts of climate change, highlighting the urgency for the state, local government and others to undertake mitigation and adaptation strategies.

Climate change refers to "a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer."
(IPCC, 2007a)

A summary of this report is available as a stand-alone document (posted at http://www.oehha.ca.gov/multimedia/epic/index.html).

IDENTIFYING AND SELECTING INDICATORS TO TRACK CLIMATE CHANGE

Environmental indicators are measurements that convey scientifically based information on the status of, and trends in, environmental conditions. 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.

A framework and process for the selection and development of indicators was adopted by the California Environmental Protection Agency (Cal/EPA) as part of the Environmental Protection Indicators for California (EPIC) Project led by the Office of Environmental Health Hazard Assessment (OEHHA) (OEHHA, 2002). The EPIC Project used this framework to identify and select indicators of climate change.

INDICATOR IDENTIFICATION

The first step under the EPIC framework is to identify issues to be characterized by the indicators. Issues identification for climate change is guided by a conceptual model of causality commonly referred to as the "***pressure-state-effects-response***" model (OECD, 1993): Human activities—as well as natural phenomena—exert ***pressures*** on the environment; these pressures alter the ***state*** or the quality and quantity of the

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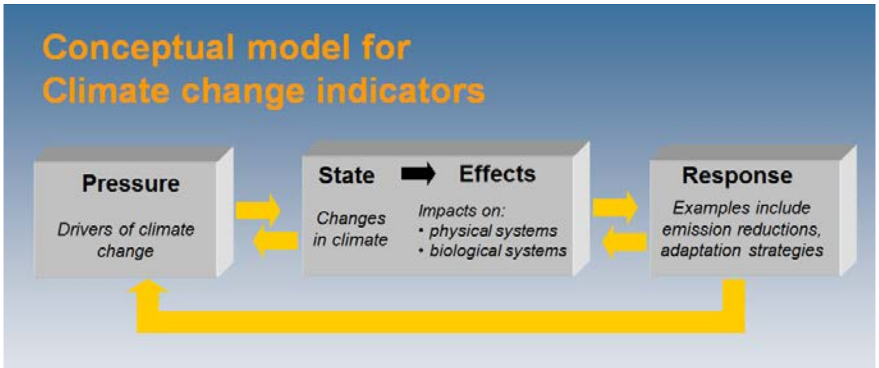
[1] Posted at: http://www.oehha.ca.gov/multimedia/epic/climateindicators.html

environment; these changes can in turn lead to adverse ***effects*** on human and ecological health. ***Responses*** are actions taken to alleviate the pressure or remediate the state.

Climate is usually defined as “average weather” and described in terms of the mean and variability of temperature, precipitation and wind over a period of time. The climate is influenced by its own internal dynamics and by external factors, both natural and human-induced. (See text box on the next page for further discussion.)



Under the pressure-state-effects-response model, factors that can alter the climate would be considered “pressures,” or **drivers of climate change** like solar radiation and changes in the composition of the atmosphere. The latter can be caused by gases and aerosols originating from natural sources (such as volcanic eruptions) and human sources (such as the combustion of fossil fuels). In this report, indicators describing drivers of climate change focus on human-influenced or anthropogenic emissions of greenhouse gases and black carbon.

Physical and biological systems on land and in oceans are already being affected by recent changes in climate, particularly regional temperature increases (IPCC, 2007a). For purposes of this report, changes to the physical characteristics of snow and ice cover, lakes and other freshwater bodies, and oceans are described using indicators of **impacts on physical systems**. Changes relating to the abundance and distribution of species and the timing of growth or life stages are described using indicators of **impacts on biological systems**. While responses—actions by governmental agencies, non-governmental organizations or society in general—are beyond the scope of this report, an overview of California laws and programs that address mitigation efforts and adaptation to climate change is provided in Appendix A.

Various sources were reviewed to identify candidate indicators that characterize:

- Human-influenced (anthropogenic) drivers of climate change
- Changes in climate
- Impacts of climate change on physical and biological systems

Sources of information consisted of peer-reviewed journals, reports published by governmental agencies, research institutions, universities and other authoritative bodies (such as the Intergovernmental Panel on Climate Change), and databases maintained by such entities. Research projects funded by the California Energy Commission’s Public Interest Energy Research Program provided notable contributions.

THE ROLE OF NATURAL CLIMATE VARIABILITY AND OTHER FACTORS

The earth's variable climate reflects the complex interactions and dependencies among the solar, oceanic, terrestrial, atmospheric and living components that make up the planet's systems. Climate processes respond to both external forces, such as anthropogenic greenhouse gases, as well as to natural modes of variability inherent to the climate system. Natural processes produce substantial seasonal, year-to-year and even decade-to-decade variations that are superimposed on the long-term warming trend, as well as substantial regional differences. It is reasonable to expect that the natural variability of the climate system can and likely will produce multi-year periods of sustained "cooling" or at least periods of no real trend even with long-term anthropogenic-forced warming (Easterling and Wehner, 2009).

Climate is typically defined based on 30-year averages. This averaging period serves to minimize the influence of natural variability on shorter time scales and facilitate the analysis of long-term trends. As stated previously, individual years or even decades can deviate from the long-term trend due to natural climate variability. Sound scientific analyses of global climate change thus tend to focus on trends over at least several decades (NRC, 2010). The frequency and magnitude of warm and cold anomalies (i.e., deviations from a long-term average) change noticeably on decadal time scales with increased warming globally (Hansen et al., 2010).

Interactions between the ocean and the atmosphere have important consequences for weather around the globe. These global-scale modes of climate variability can shift weather patterns and disrupt local climate processes. The El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are important cyclical climate phenomena that influence many physical and biological processes in the Pacific Ocean (Appendix B). It is difficult to establish when ocean-related influences on marine populations are due to climate change or natural variability in ENSO and PDO processes. The lack of long-term monitoring of ocean conditions and concurrent marine population changes often limits the ability to discern real trends and possible links to climate change.

In addition to natural climate variability, other factors contribute to uncertainty when evaluating potential climate change impacts. The impacts depend on how climate change interacts with other global and regional environmental changes, including changes in land use, management of natural resources, and environmental pollution. For example, the ocean is affected by human activities such as fishing, habitat destruction, pollution and species introductions that may be masking more subtle impacts of climate change. In fact, researchers may have been at times misled to interpret climate change impacts as those of local environmental changes. As one scientist notes, "The difficulty of disentangling multiple stressors within poorly sampled systems has stymied the discovery of marine climate change impacts" (Richardson and Poloczanska, 2008).

INDICATOR SELECTION

Indicators selected must be derived from scientifically acceptable data that support sound conclusions about the system being studied (OEHHA, 2002). In addition, the indicators must closely represent the issue, be sufficiently sensitive to detect changes in conditions, and provide meaningful basis for decision-making.

Indicator selection criteria

- ✓ ***Data quality***
  Data are collected using scientifically valid data methods and can support sound conclusions
- ✓ ***Representativeness***
  Indicator reflects the issue it is intended to characterize
- ✓ ***Sensitivity***
  Indicator can distinguish meaningful differences in conditions
- ✓ ***Decision-support***
  Indicator provides useful information for decision-making

Making a determination that these criteria are met is relatively straightforward for those indicators describing drivers of climate change and changes in climate. However, determining whether a candidate indicator is representative of an impact of climate change requires additional considerations. Specifically, attributing observed impacts to human-influenced changes in climate presents a challenge. Such impacts—particularly those describing ecological responses—are often influenced by many other non-climatic factors such as land use, management of natural resources, and emissions of pollutants. Further, even when impacts have a demonstrated link to climate, it can be difficult to distinguish human-induced changes to climate from natural climate variability. (CCSP, 2008)

For purposes of this report, when an association between an effect and a climate parameter (most often temperature) has been demonstrated, that effect is considered to represent an indicator of the impacts of climate change. Likewise, an effect is included as an indicator when evidence is presented that it is consistent with an expected response to climate change. Effects or changes for which plausible hypotheses of the influence of climate change have been presented but which have not yet been supported by data will be tracked as "emerging issues." These issues are discussed in the final chapter of this report (see page 223).

As a final step, selected indicators are classified into three categories based on the availability of data: ***Type I***, adequate data are available, supported by ongoing, systematic monitoring or collection; ***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; and ***Type III***, conceptual indicators for which no ongoing monitoring or data collection is in place.

The indicators selected to characterize climate change in California are listed on the next page. In addition to these indicators, this report presents a brief discussion of ***emerging issues***. These are changes or impacts that are plausibly influenced by climate change, but for which sufficient data to establish such influence is not yet available.

INDICATORS OF CLIMATE CHANGE IN CALIFORNIA*

CLIMATE CHANGE DRIVERS

- Greenhouse gas emissions *(updated)*
- Atmospheric greenhouse gas concentrations *(updated)*
- Atmospheric black carbon concentrations *(new)*
- Acidification of coastal waters (Type II) *(new)*

CHANGES IN CLIMATE

- Annual air temperature *(updated)*
- Extreme heat events *(updated)*
- Winter chill *(updated information)*
- Freezing level elevation *(new)*
- Annual precipitation *(updated)*

IMPACTS OF CLIMATE CHANGE

On physical systems

- Annual Sierra Nevada snowmelt runoff *(updated)*
- Snow-water content *(updated)*
- Glacier change *(updated information)*
- Sea level rise *(updated)*
- Lake water temperature *(updated)*
- Delta water temperature *(updated)*
- Coastal ocean temperature *(updated)*
- Oxygen concentrations in the California Current *(no update)*

On humans

- Mosquito-borne diseases (Type II) *(updated information)*
- Heat-related mortality and morbidity (Type II) *(updated information)*
- Exposure to urban heat islands (Type III) *(new)*

On vegetation

- Tree mortality *(updated information)*
- Large wildfires *(updated information)*
- Forest vegetation patterns *(no update)*
- Subalpine forest density *(new)*
- Vegetation distribution shifts *(new)*
- Alpine and subalpine plant changes (Type II) *(no update)*
- Wine grape bloom (Type II) *(updated information)*

On animals

- Migratory bird arrivals *(no update)*
- Small mammal range shifts *(no update)*
- Spring flight of Central Valley butterflies *(updated)*
- Effects of ocean acidification on marine organisms (Type III) *(new)*
- Copepod populations *(updated)*
- Sacramento fall run Chinook salmon abundance *(new)*
- Cassin's auklet populations *(updated)*
- Shearwater and auklet populations off Southern California *(new indicator)*
- Sea lion pup mortality and coastal strandings *(new)*

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* [1] Unless otherwise noted, the environmental indicator is classified as "Type I".

[2] Each indicator is followed by a parenthetical describing its status relative to the 2009 report, as follows:

Updated: Both graph and narrative have been updated.

Updated information: New information is presented, but the graph is unchanged.

No update: Same graph and narrative from 2009 report are presented.

New: Indicator did not appear in the 2009 report.

References:

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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 greenhouse gases or aerosols from fossil fuel combustion are human-induced forcings (IPCC, 2007a).

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, 2007a).

INDICATORS: CLIMATE CHANGE DRIVERS

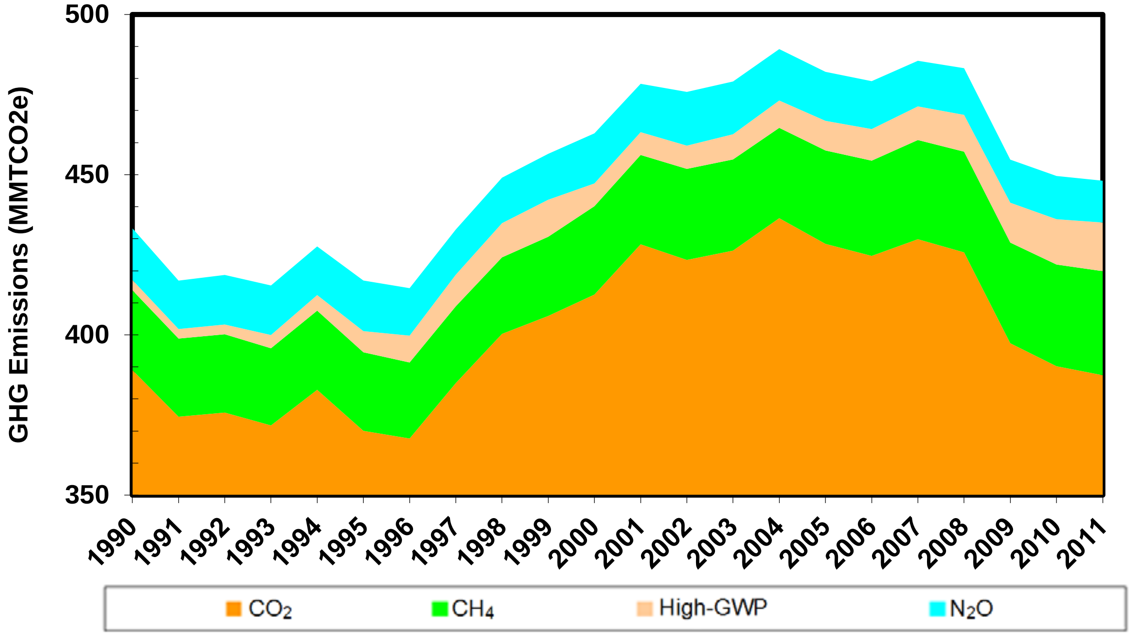
Greenhouse gas emissions *(updated)*
Atmospheric greenhouse gas concentrations *(updated)*
Atmospheric black carbon concentrations *(new)*
Acidification of coastal waters *(new)*

Reference:
IPCC (2007a). *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*. http://www.ipcc.ch/ipccreports/assessments-reports.htm

GREENHOUSE GAS EMISSIONS (UPDATED)

Overall, total emissions of greenhouse gases have increased since 1990.

Total Emissions by Pollutant
Total California Greenhouse Gas Emissions in CO_2 Equivalents: 1990-2011
(Based on IPCC Second Assessment Report 100-year Global Warming Potential)



***MMTCO$_2$e** = million metric tons of carbon dioxide equivalents

Source: ARB, 2013

What is the indicator showing?

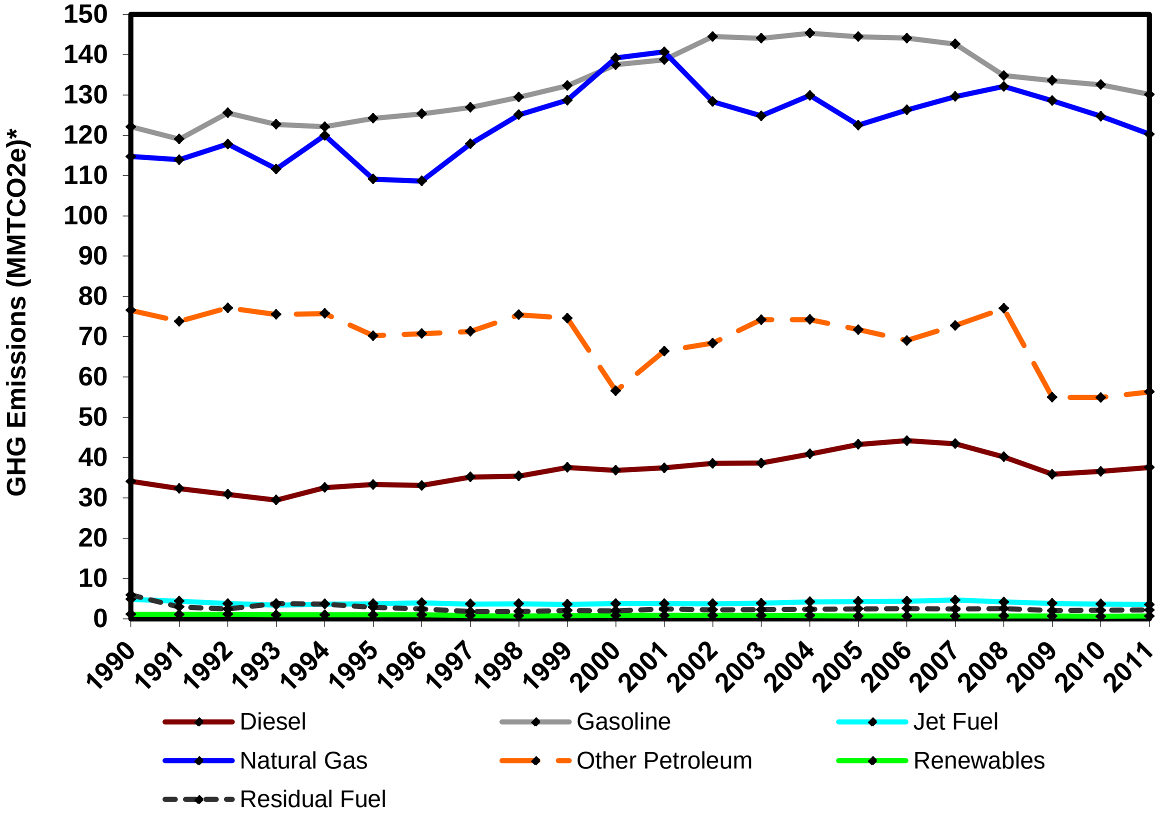
California cumulative emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and high global warming potential (High-GWP) gases, expressed in CO_2 equivalents (million metric tons of carbon dioxide equivalents; MMTCO2e), have seen an overall increase between 1990 and 2011. In the past five years, however, emissions have generally been declining. 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. Greenhouse gas emissions also occur from non-combustion activities at landfills, wastewater treatment facilities and from certain agricultural operations. Carbon dioxide accounts for the largest proportion of GHG emissions (averaging 88 percent of total GHG emissions since 2000). In comparison, CH_4 accounted for about 6 percent of the State's total GHG emissions from 2000 through 2011; N_2O accounted for approximately 3 percent (ARB, 2013).

What are "CO_2 equivalents"?

Emissions of greenhouse gases other than carbon dioxide (CO_2) are converted to **carbon dioxide equivalents** or **CO_2e** based on their Global Warming Potential (GWP). GWP represents the warming influence of different greenhouse gases relative to CO_2 over a given time period and allows the calculation of a single consistent emission unit, **CO_2e**.

GREENHOUSE GAS EMISSIONS BY FUEL

Greenhouse Gas Emissions by Fuel Type: 1990 - 2011
(Based on IPCC Second Assessment Report 100-year Global Warming Potential)



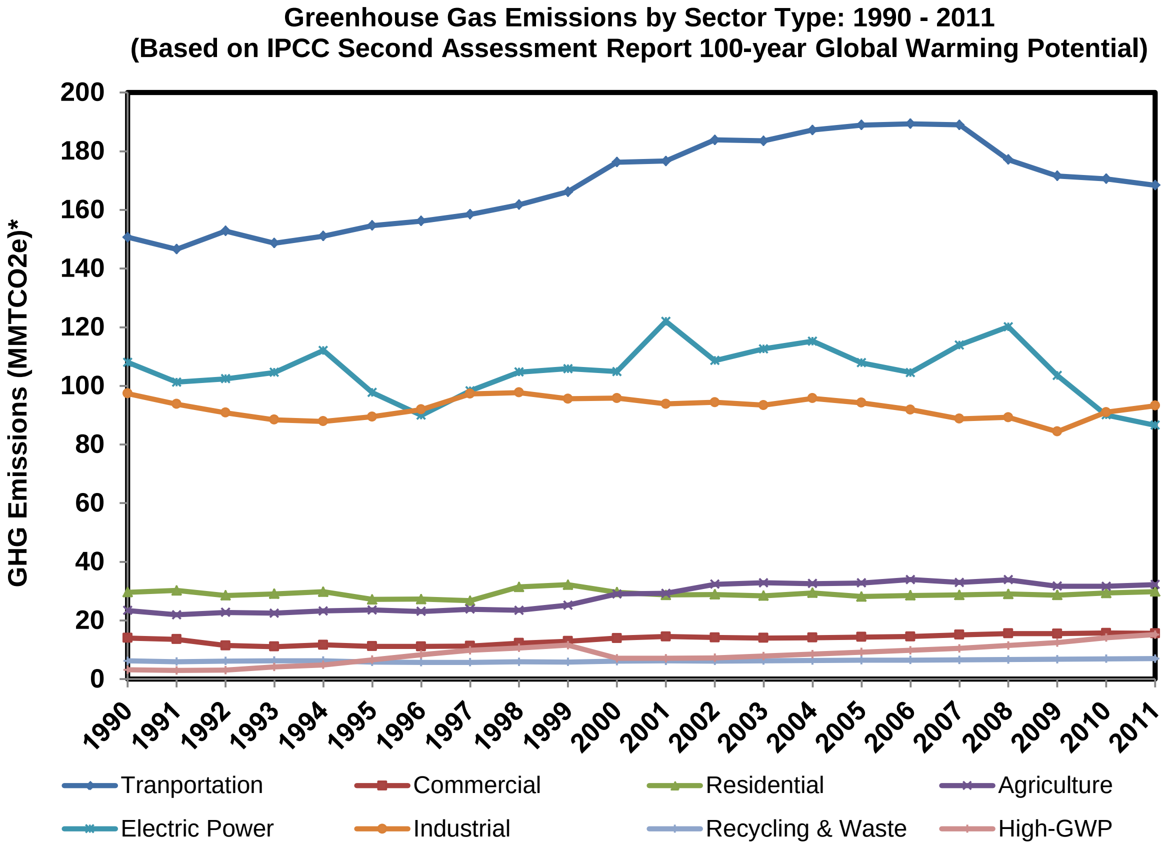
***MMTCO$_2$e** = million metric tons of carbon dioxide equivalents

Source: ARB, 2013

What is the indicator showing?

Greenhouse gas emissions from the combustion of different fuels vary by fuel type. Non-renewable fossil fuels are used more than any other fuel type in California. Renewable fuels include biomass, which consists of wood and wood waste, municipal solid waste, landfill gas, and wastewater digester gas. Residual fuel refers to the heavier fuel oils that remain after the distillate oils and lighter hydrocarbons are removed through the refining process. Residual fuel is typically used for space heating, vessel bunkering, and to fuel various industrial processes. Other Petroleum is a general classification that includes aviation gasoline, coal, crude oil, liquefied petroleum gas, propane, tires, and waste oil.

Greenhouse Gas Emissions by Sector


Greenhouse Gas Emissions by Sector Type: 1990 - 2011
(Based on IPCC Second Assessment Report 100-year Global Warming Potential)

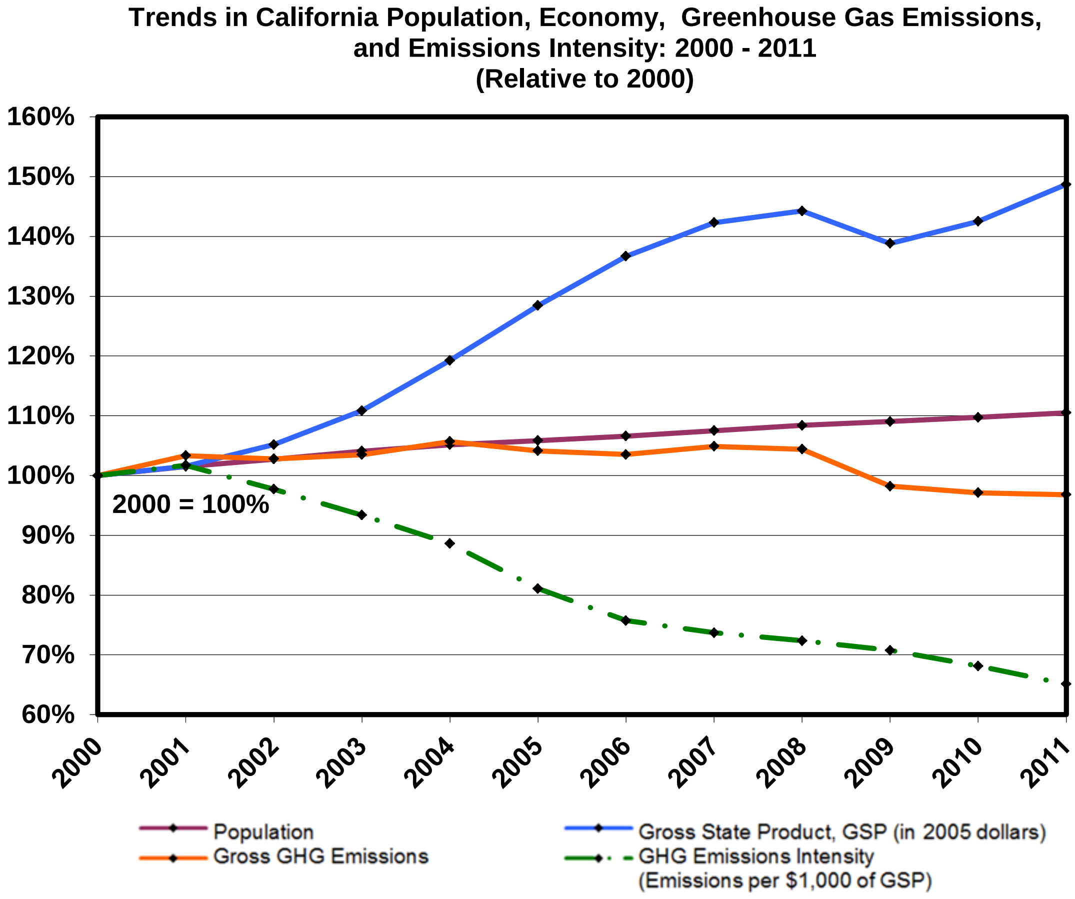
***MMTCO$_2$e** = million metric tons of carbon dioxide equivalents

Source: ARB, 2013

What is the indicator showing?

Emission inventories are a systematic listing of emitting categories with an estimate of the amount of emissions from each category over a given time period. A common categorization approach consists of using economic sectors to apportion emissions. Emissions of GHGs have increased for most of California's major economic sectors, with the largest increase in total emissions occurring from transportation. The transportation sector, which accounts for nearly 40 percent of the state's total emissions, includes emissions from on- and off-road mobile sources, aviation, rail, and shipping. California's transportation fuel use increased most years between 1990 and 2007, and has generally been decreasing since 2007. The industrial sector accounts for an average of 21 percent of total statewide emissions since 2000, and electricity generation for about 23 percent, with almost equal contributions from in-state and imported electricity. The High-GWP sector refers to emissions from the use of High-GWP gases in all other sectors. By combining emissions from High-GWP gases in one category, the emission trend from the use of these gases—and their potential reduction over time—is more easily visualized.

TRENDS IN CALIFORNIA POPULATION, ECONOMY, AND GREENHOUSE GAS EMISSIONS



Source: ARB, 2013

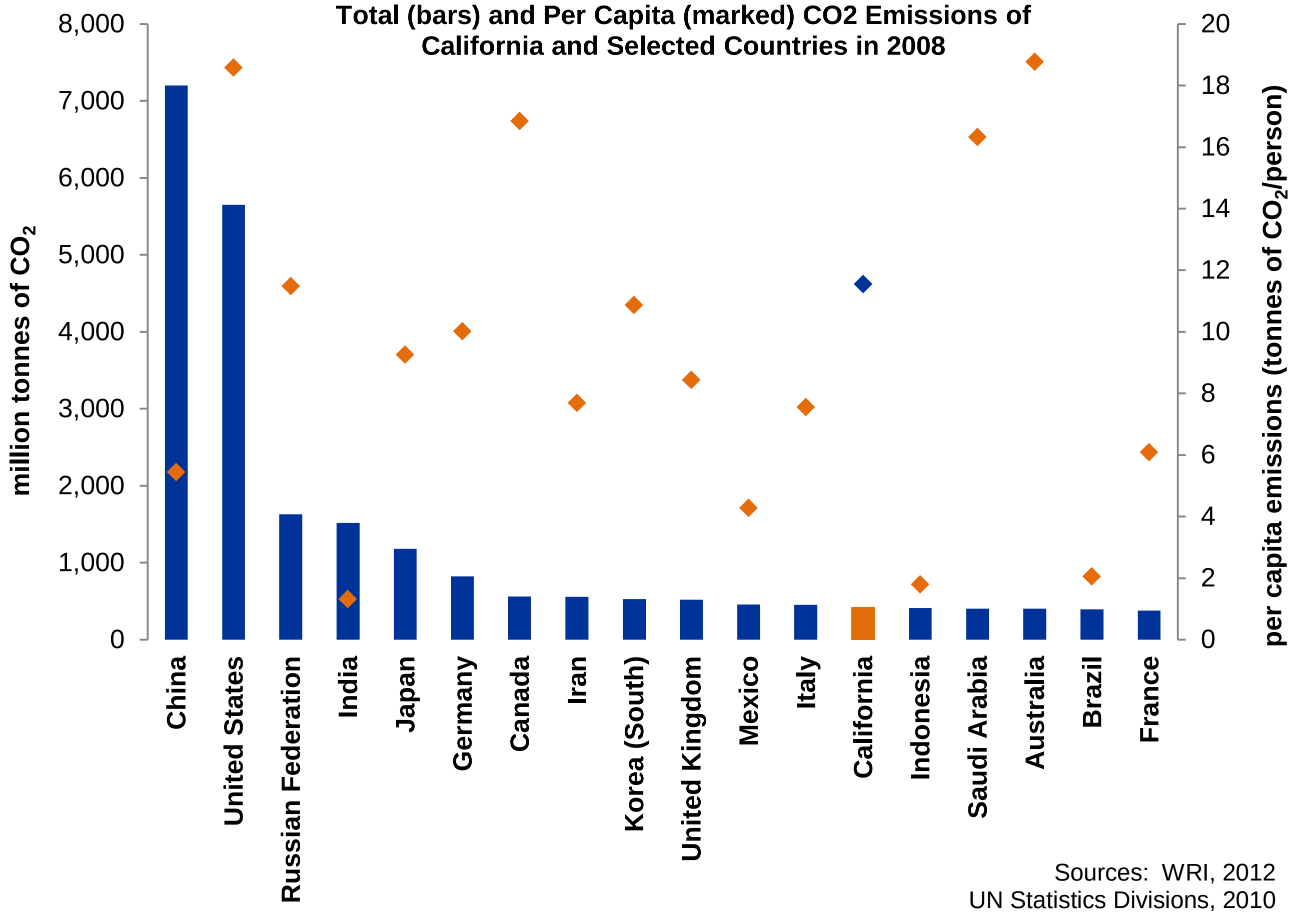
What is the indicator showing?

Emissions per $1,000 of gross state product (GSP) (represented by GHG Emissions Intensity) have decreased from 2000 through 2011, while the State's population has steadily increased by 10 percent and the GSP has increased overall by 49 percent (ARB, 2013).

Total California GHG emissions have increased by 3 percent from 1990 to 2011 (see page 7); however, emissions decreased by more than 7 percent from 2008 to 2011 with most of the decrease occurring between 2008 and 2009. The emissions decrease between 2008 and 2011 likely occurred as a result of the economic recession that began in late 2007.

The emissions of GHG per unit of California's economic output, or gross state product (GSP), have decreased substantially between 2000 and 2011 (ARB, 2013). The GSP is a measure of the economic output of California and is estimated by summing the values of goods and services provided within the boundaries of California.

TOTAL AND PER CAPITA CO_2 EMISSIONS OF CALIFORNIA



Sources: WRI, 2012
UN Statistics Divisions, 2010
US Census Bureau, 2010

What is the indicator showing?

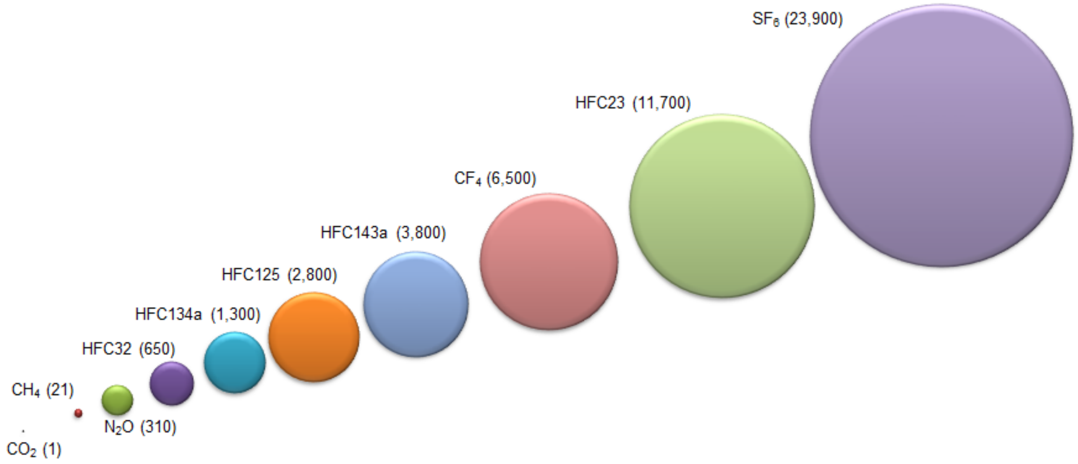
California's average per capita emissions of CO_2 are lower than the average for the United States and several other nations (WRI, 2012). The top 10 emitting nations account for more than three-quarters of the total global CO_2 emissions in 2008. If California was a country, it would rank 13th highest in CO_2 emissions worldwide (WRI, 2012).

Why are these indicators important?

Atmospheric concentrations of greenhouse gases have increased since the Industrial Revolution, enhancing the heat-trapping capacity of the earth's atmosphere. Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and high global warming potential (High-GWP) gases. Carbon dioxide emissions from the combustion of fossil fuels account for the largest proportion of GHG emissions, while High-GWP gases account for about 2 percent annually.

To account for the total GHG emissions, non-CO_2 emissions are converted to carbon dioxide equivalents (CO_2e). The conversion uses the Global Warming Potential (GWP), which indexes the radiative forcing of a particular GHG to the reference value established for CO_2 (radiative forcing is a measure of the extent to which an agent–such as a particular GHG–can alter the heat balance of the Earth). Current standard practice for GHG inventories uses 100 years as the time horizon for calculating GWPs.

As illustrated in the diagram below, CO_2 has the lowest GWP of all GHG reported in the statewide GHG inventory. The chemical absorption properties of High-GWP gases can have a large effect on atmospheric conditions. For example, the GWP of SF_6 is 23,900 meaning that one ounce of SF_6 has the same warming effect as 1,494 pounds of CO_2.



Global Warming Potential of Greenhouse Gases

Accurately tracking GHG emission trends in California allows policymakers to make well informed decisions and assess climate change patterns. Businesses that track their GHG emissions can better understand their processes which emit GHG, establish an emissions baseline, determine the carbon intensity for their operations, and evaluate potential GHG emission reduction strategies.

Climate Change Policies

California's climate program has evolved through a series of statutory requirements and executive orders over more than 20 years. Most notably, California established the nation's first comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective GHG reductions 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 2006, by Executive Order, Governor Arnold Schwarzenegger 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 California Air Resources Board (ARB).

In 2007, ARB adopted the Regulation for Mandatory Reporting of Greenhouse Gas Emissions in order to track the State's progress in meeting GHG target levels pursuant to AB 32. The first mandated GHG reporting program of its kind in the United States, the regulation requires emission sources to annually report their GHG emissions. In 2009, approximately 600 California facilities began reporting their GHG emissions to ARB.

Pursuant to AB 32, ARB has also developed a market-based cap-and-trade program for reducing GHG emissions. Under this economy-wide program, an overall limit on GHG emissions from capped sectors will be established and facilities subject to the cap will be able to trade permits (allowances) to emit GHG. California is also participating in the Western Climate Initiative (established in 2007) along with Quebec, Canada. The Initiative is working towards consistent GHG reporting standards and is in the process of creating a GHG emissions trading market for North America.

What factors influence these indicators?

Statewide CO_2 emissions reflect fossil fuel consumption across all major economic sectors, which in turn are influenced by population growth, vehicle miles traveled, 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, and can also boost commercial vehicle miles traveled. The dominant fuels combusted are natural gas (used primarily for in-state electricity generation and for residential and industrial uses) and gasoline (for transportation purposes).

California's population has grown steadily from 1990 through 2011; this typically 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 similar to population growth (26 percent), with a total increase of 25 percent from 1990 through 2011 (CEC, 2013). Residential and industrial natural gas use increased slightly from 1990 to 2011, while commercial natural gas use increased by 19 percent. The reduction in natural gas consumption in the State is an indication, among other factors, of more stringent building code standards enacted since 1975 for residential and commercial construction (e.g., insulation thickness, window design, lighting systems, and heating/cooling equipment specification). Energy efficiency practices have also led to a decrease of electricity consumption by the industrial sector by 17 percent between 1990 and 2011 (CEC, 2013).

The per capita electricity consumption for California is the second lowest in the nation, primarily due to mandated energy efficiency programs (EIA, 2013). The significant declining trend in CO_2 emissions per Gross State Product (GSP) is an indication of higher energy efficiency over time, 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 states.

California is one of the largest producers of crude oil in the United States (EIA, 2013). California oil refineries are subject to state laws which are more stringent than federal requirements for fuel parameters such as sulfur content, nitrogen content, oxygen content, and carbon intensity (ARB, 2013). Concerns over offshore oil and gas development (along with previous marine oil spills) have led to a permanent moratorium on new offshore drilling and leases in California waters. However, this moratorium does not affect previous drilling leases and a federal moratorium on oil and gas leases in federal outer continental shelf waters expired in 2008 (EIA, 2013).

Electricity Generation was the second highest emitting sector for 1990 through 2011, although emissions from the sector have declined overall from 1990 to 2011 by approximately 20 percent (ARB, 2013). Natural gas power plants account for approximately 50 percent of in-state electricity generation. Nuclear power made up about 18 percent[*] of electrical generation in California. Hydroelectric sources in California account for 6 percent of the nation's hydroelectric power and generate about 15 percent of the state's electricity (CEC, 2013). Other renewable energy sources used in the State include wind, geothermal, solar, and waste products. California is also the top producer of geothermal energy and wind power in the nation (EIA, 2013). In 2006, California amended its Renewable Portfolio Standards for electricity utilities to require at least 20 percent retail power sales from renewable resources by 2010 and 33 percent by 2020. And, to encourage the installation of rooftop solar power, protect against power outages, upgrade transmission systems, and to encourage energy conservation, the California Energy Action Plan and Solar Initiative were enacted by legislation (CEC, 2012).

Because of high electricity demand, more electricity is imported to California than in other states. A portion of these imports consist of power from hydroelectric sources as well as from coal-fired energy plants. Coal power generation results in greater CO_2 emissions than that from other fuels used to produce electricity. A recent California law prohibits power utilities from entering into new long-term contracts with conventional coal-fired power producers (EIA, 2013).

To meet the State's increasing 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

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[*] In 2012, this percentage dropped to about 9 percent. The San Onofre Nuclear Generation Station (SONGS), which had provided nuclear power to the state for over 40 years, went offline in January 2012. In June 2013, Southern California Edison announced plans to permanently retire SONGS.

many existing power plants in operation and thereby produce less CO_2 emissions per unit of electricity generated.

Unlike residential electricity use, the overall increase in passenger vehicle fuel consumption was similar to population growth from 1990 to 2007, and has shown a decrease between 2008 and 2011 (ARB, 2013). The majority of CO_2 emission sources in California are generated from transportation activities and electrical power generation. Although California's vehicle population grew during that period, other factors also affected the growth in consumption of transportation fuels, most notably fuel prices and vehicle choice. For instance, high fuel prices correlated with greater fuel conservation and the selection of more fuel-efficient vehicles.

The implementation of strategies adopted pursuant to the California Sustainable Communities and Climate Protection Act of 2008 (SB 375) will enhance the state's ability to reach its GHG emission reduction targets. SB 375 encourages better integration of transportation and land use planning in ways that reduce GHG emissions. It requires ARB to develop regional GHG emission reduction targets for passenger vehicles for 2020 and 2035 for each of the State's 18 metropolitan planning organizations. Each metropolitan planning organization develops its own unique plan, known as a Sustainable Communities Strategy, for meeting its target through a locally-driven process. The plans can include any combination of land use strategies, transportation system improvements, and transportation-related measures or policies developed at the local and regional level to meet the targets.

Technical Considerations

Data Characteristics

A GHG inventory is an estimate of the amount of GHG emitted or removed over a specified area and time period from known sources or categories of sources.

Emission inventories generally use one of two basic approaches to estimate emissions. The first may be referred to as a top-down approach, which uses state, regional, or national level data. An example is the use of statewide fuel consumption to estimate CO_2 emissions for a particular category of emissions, such as petroleum refining. The second approach to developing an emission inventory 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. This is often referred to as a bottom-up inventory approach. In either approach, calculation methodologies typically reference the 2006 IPCC Guidelines for National Greenhouse Gas Inventories or the U.S. EPA's national GHG inventory.

To examine climate processes and aid in improving GHG emission inventories, ARB is conducting research projects on atmospheric concentrations of GHG pollutants. Ambient monitoring in 2008 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). Ambient air sampling for GHG compounds has also been performed in 2008 at the Walnut Grove transmission tower south of Sacramento.

Further, aircraft and ocean vessel studies are being completed for California areas (in collaboration with the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and CEC) from 2008 through 2010 in order to obtain atmospheric GHG samples and other data collection for ozone, cloud properties, aerosols, black carbon, and to observe changes in sea ice and glaciers. Studies have shown that evaluation of ambient measurement data can be an indicator of GHG compound concentrations in the atmosphere. 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. The inventory, however, excludes emissions that occur outside California during the manufacture and transport of products and services consumed within the State. The California inventory also contains transportation-related emissions from in-state aviation and rail as well as internationally-flagged ships within California ocean waters provided that either their origin or destination is a California port.

The electricity sector does include 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.

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 refined by conducting research and related sampling activities. Consistent methods are important as California considers participation in standardized regional, national, and international GHG emission reduction programs.

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California Department of Finance (2007). State Population Estimates: Table E-4 Historical Population Estimates for Cities, Counties and State, 1990-2000 with 1990 and 2000 Census Counts
http://www.dof.ca.gov/research/demographic/reports/estimates/e-4/1991-2000/documents/E-4_90-00_Rpt.XLS

California Department of Finance (2012). State Population Estimates: Table E-4 Population Estimates for Cities, Counties and State, 2001-2010 with 2010 Census Counts
http://www.dof.ca.gov/research/demographic/reports/estimates/e-4/2001-10/view.php

California Department of Finance (2013). State Population Estimates: Table E-6 Population Estimates for Cities, Counties and State, 2011
http://www.dof.ca.gov/research/demographic/reports/estimates/e-6/

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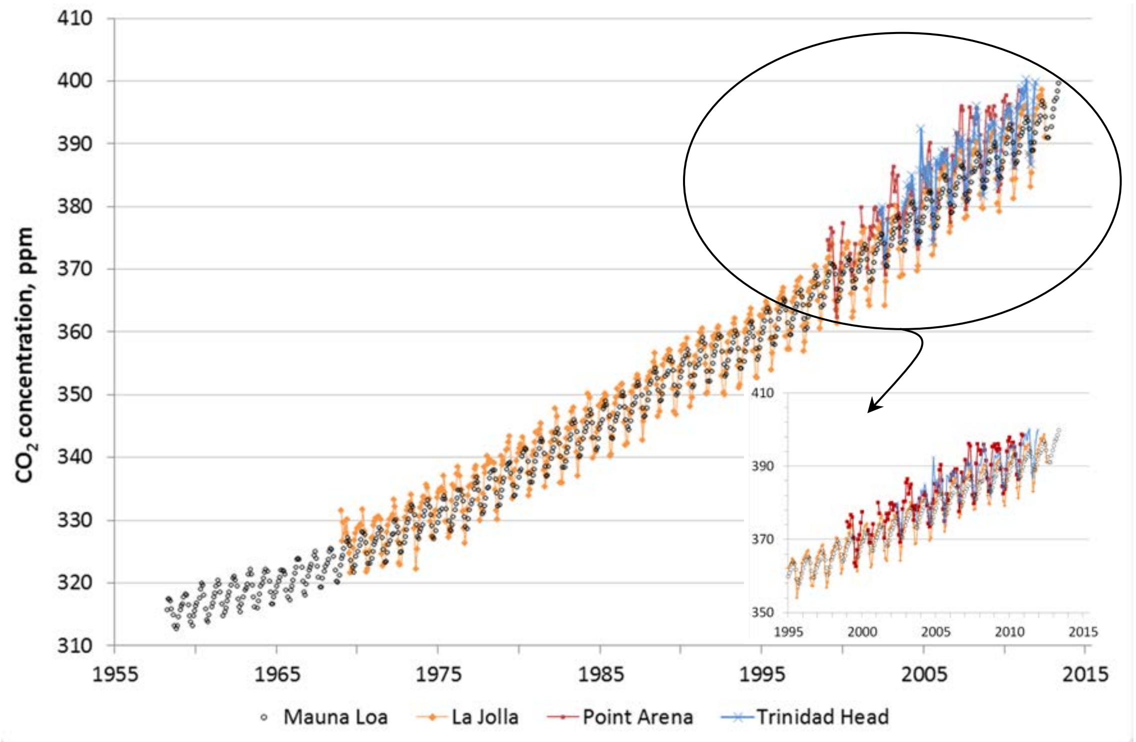
ATMOSPHERIC GREENHOUSE GAS CONCENTRATIONS (UPDATED)

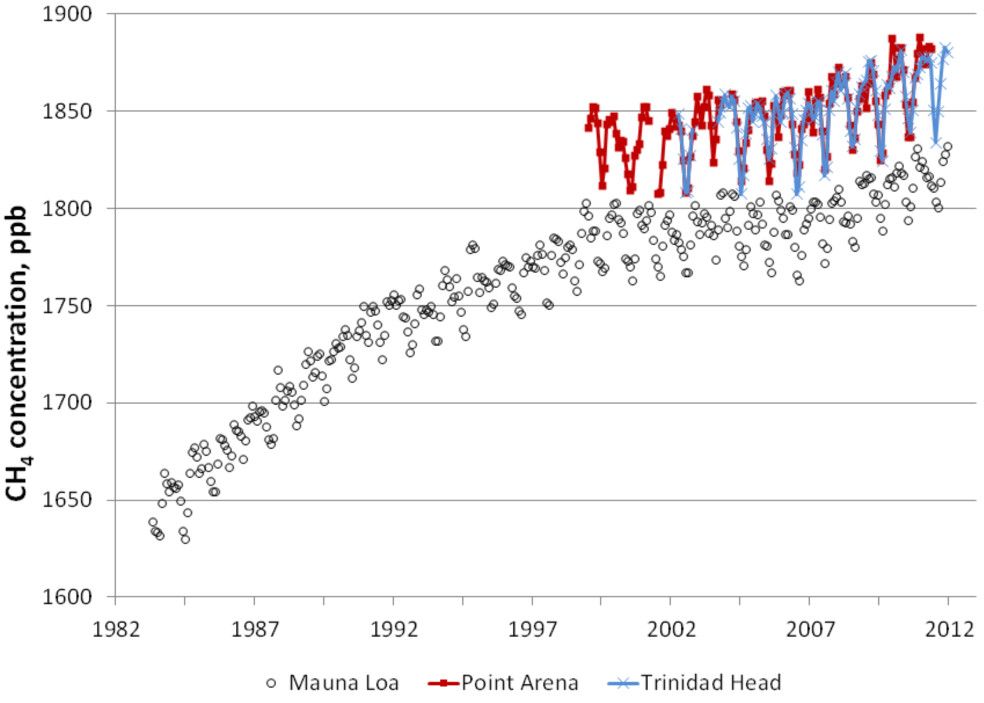
Concentrations of the greenhouse gases carbon dioxide and methane in the atmosphere are increasing in California, consistent with global trends.

Monthly average atmospheric carbon dioxide concentrations



Sources: NOAA, 2013a and Conway, et al. 2011 (Mauna Loa, Point Arena and Trinidad Head); SIO, 2012 (La Jolla)

Monthly average atmospheric methane concentrations

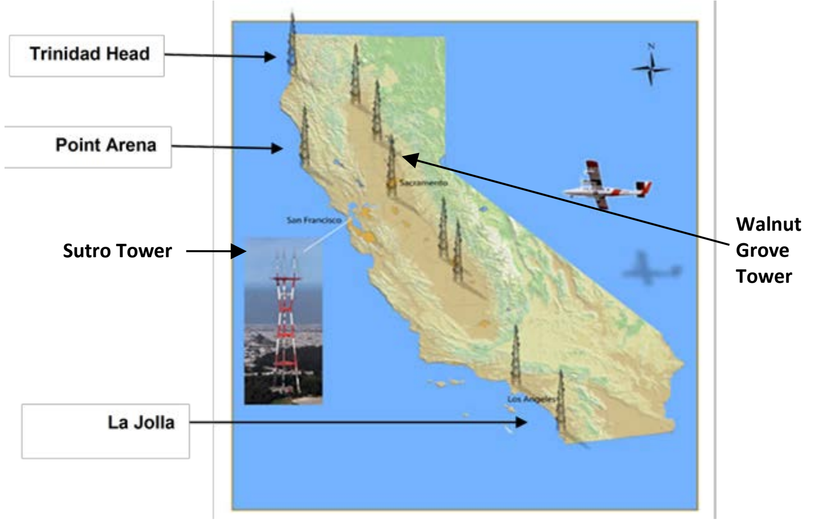


Source: NOAA, 2013a and Dlugokencky et al., 2011

What is the indicator showing?

Atmospheric concentrations of greenhouse gases are increasing at coastal sites in California, closely tracking global levels, as represented by the measurements at Mauna Loa, Hawaii. The first graph shows carbon dioxide (CO_2) measurements at four sites: long-term measurements at La Jolla, which began in 1969, and at Mauna Loa, the longest record of direct atmospheric measurements of CO_2; and more recent measurements at Trinidad Head and Point Arena, which began in 1999 and 2002, respectively. At all three California sites, the measurements are, on average, slightly higher and exhibit a wider range of values than those at Mauna Loa. On May 9, 2013 (not shown on the graph), the daily mean concentration of CO_2 at Mauna Loa peaked above 400 ppm for the first time since measurements began in 1958 (NOAA, 2013). By comparison, the pre-industrial CO_2 concentrations were about 280 ppm (WMO, 2012).

Greenhouse gas monitoring locations in California



Source: Lawrence Berkeley Laboratory

The second graph shows increasing atmospheric concentrations of methane (CH_4) at Mauna Loa since1983, and at Point Arena and Trinidad Head since 1999 and 2002, respectively. During 1999 to 2006, CH_4 levels were relatively constant before increasing again in 2007.

The CH_4 measurements at the California sites are higher than those at Mauna Loa. This is not surprising, as CH_4 concentrations exhibit a strong latitudinal gradient (that is, concentrations are higher in northern latitudes, decreasing as one moves south); nevertheless, the higher levels at the California sites may be indicative of local influences. The highest monthly average concentration of CH_4 shown on the graph at Mauna Loa was 1832 ppb in December 2011; 1880 ppb at Trinidad Head in November 2011; and 1882 ppb at Point Arena in December 2010. Pre-industrial CH_4 concentrations were about 700 ppb (WMO, 2012).

Why is this indicator important?

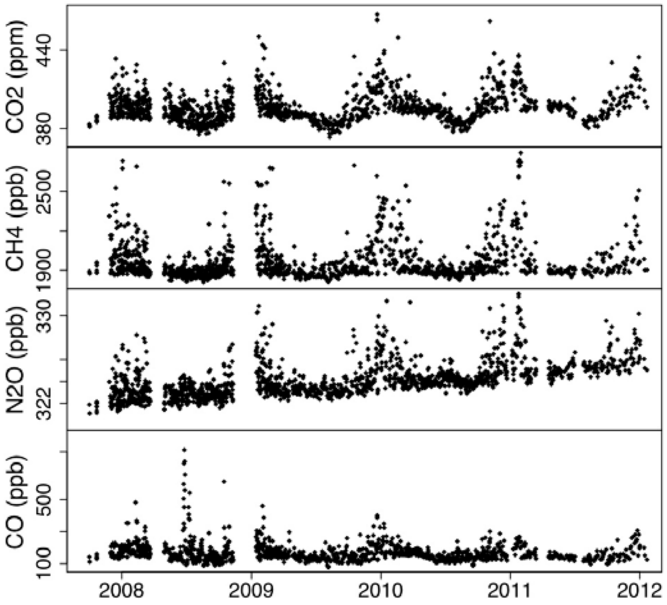
CO_2 and CH_4, along with nitrous oxide, chloroflourocarbons, hydrochlorofluorocarbons, perfluorocarbons and sulfur hexafluoride, are long-lived greenhouse gases (GHGs) considered to be the largest and most important anthropogenic driver of climate change. CO_2 is responsible for 64 percent of the total radiative forcing caused by long lived GHGs, while CH_4 contributes about 18 percent (WMO, 2011). (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. Radiative forcing values are for changes relative to preindustrial conditions defined at 1750 and are expressed in watts per square meter.)

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^{o}N), 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" (CCSP, 2007; IPCC, 2007b). Tracking the movement and accumulation of carbon in these reservoirs provides information necessary for formulating mitigation strategies. Data on atmospheric GHG levels, in particular, are needed for projecting future climate change associated with various emission scenarios, and for establishing and revising emission reduction targets (IPCC, 2007c).

To evaluate the local to regional GHG emissions from California, the Lawrence Berkeley Laboratory and the Global Monitoring Division of the National Oceanic and Atmospheric Administration began the California Greenhouse Gas Emission Measurement Project with support from the California Energy Commission's Public Interest Environmental Research program. The project has been monitoring atmospheric concentrations of major GHGs since 2007 at two California sites in Central California (Fischer et al., 2009).

Greenhouse gases at Walnut Grove Tower
(near Sacramento)



Source: M. L. Fischer, personal communication, 2011

Concentrations of CO_2, CH_4, and N_2O, are typically enhanced significantly above background values from the regional GHG sources in California. For example, the figure at the right shows measured mixing ratios of CO_2, CH_4, and N_2O, and CO (a tracer of combustion) from a tall television-transmission tower near Walnut Grove, CA. Atmospheric measurements from these inland towers have been combined with boundary oceanic conditions and meteorological predictions of atmospheric gas transport to infer the most likely distribution and magnitude of regional land surface CH_4 emissions from Central California (Zhao et al., 2009). In collaboration with California EPA, this work is now being extended to include other measurement sites and GHGs.

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, 2007c). 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 over 380 ppm today (WMO, 2011; Tans and Keeling, 2012). 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).

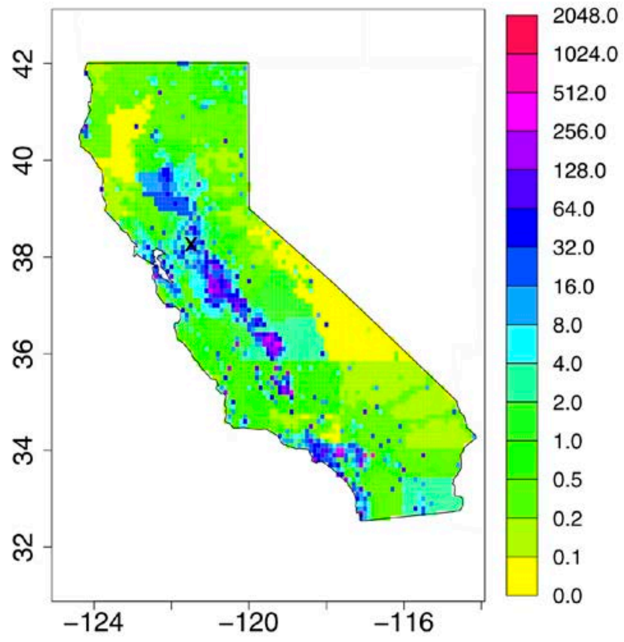
While more than half of emitted CO_2 is currently removed within a century, about 20 percent remains in the atmosphere for many millennia. Consequently, atmospheric CO_2 will continue to increase in the long term even if its emission is substantially reduced from present levels. It should be noted that, 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, 2007d).

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).

Atmospheric methane originates from both natural and anthropogenic sources. Methane is emitted from wetlands, oceans, termites and geological sources. Anthropogenic sources of methane include rice agriculture, livestock, landfills and waste treatment, biomass burning and fossil fuel exploitation (i.e., extraction, transmission, distribution and use). The production of methane by many of these sources involves anaerobic fermentation processes, and climate variables—notably temperature and moisture—have been shown to influence production and emission of methane from these sources. Oxidation processes remove methane from the atmosphere—a process likewise affected by climate variables. Once emitted, methane remains in the atmosphere for about 8 years before removal (IPCC, 2007b; IPCC, 2007c).

The map on the right shows annual mean methane emissions from *a priori* emissions model updated from Zhao, Andrews et al. (2009) to include major known sources such as livestock, landfills, rice agriculture, wetlands, and natural gas and petroleum infrastructure (Fischer, personal communication, 2011).

Annual mean methane emissions* (nmol m^{-2} s^{-1})



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*From a priori emissions model updated from Zhao et al., 2009; at 0.1 degree (~10 km) spatial resolution.

Source: M. L. Fischer, personal communication, 2011

Technical Considerations

Data Characteristics

The CO_2 data presented above are a combination of data from the Scripps Institution of Oceanography (SIO), the Lawrence Berkeley National Laboratory, and the National Oceanic and Atmospheric Administration's (NOAA) Earth System Research Laboratory (ESRL). In particular, NOAA-ESRL leads the Carbon Cycle Cooperative Global Air Sampling Network, an international effort which includes regular discrete samples from baseline observatories, cooperative fixed sites and commercial ships (NOAA, 2013b). 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. The measurements for Mauna Loa include data (from March 1958 through April 1974) obtained by C. David Keeling of SIO (Conway et al., 2011). In general, the data for the last year are subject to change, depending on quality control procedures; data for earlier years may occasionally be changed for the same reason. Such changes are usually minor.

At the 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. 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 et al., 2001).

CH_4 data are also from the NOAA ESRL network. Methane is detected using flame ionization detection. Monitoring at Mauna Loa began in 1983, Point Arena in 1999, and Trinidad Head in 2002.

Strengths and Limitations of the Data

NOAA ESRL data undergo critical evaluation for quality control (NOAA, 2013c). 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 .

To extend long-term carbon-cycle gas monitoring to continental areas, 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, 2013d). As mentioned above, the Lawrence Berkeley National Laboratory, NOAA-ESRL began monitoring at the two California towers (in Walnut Grove and at Sutro Tower above San Francisco). The work is supported by the California Energy Commission, the California Air Resources Board, and the US Department of Energy. Both sites are instrumented with automated flask sampling systems that provide daily measurements of a suite of greenhouse gases as well as other compounds including radiocarbon CO_2 (a tracer of fossil fuel CO_2 additions to the atmosphere). The Walnut Grove site is the first tall tower site with continuous CH_4 measurements, while the San Francisco site at Sutro Tower is the first site located in an urban center.

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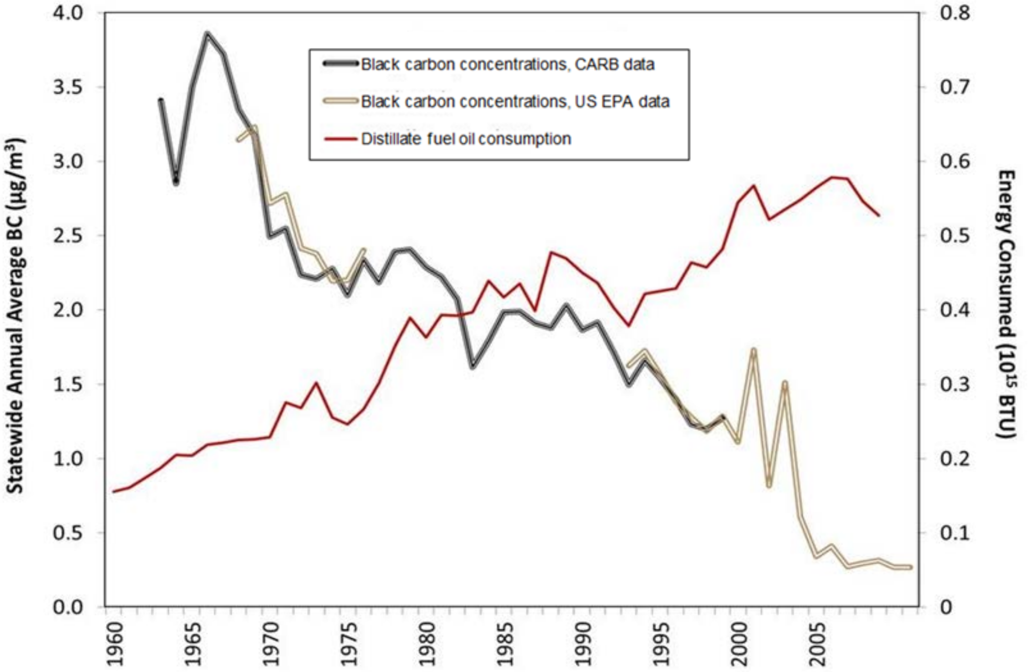
Climate change drivers

ATMOSPHERIC BLACK CARBON CONCENTRATIONS (NEW)

Statewide levels of black carbon, a major short-lived contributor to climate change, have decreased by about 90 percent over the past 45 years.

Statewide annual average concentrations* of black carbon and distillate fuel oil (including diesel fuel) consumption



Source: V. Ramanathan et al (2013)

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*Concentrations shown after 2000 are based on limited data and may not represent statewide concentrations (see Technical Considerations).

What is the indicator showing?

Annual-average black carbon (BC) concentrations in California have dropped markedly over the past 45 years, from nearly 4 micrograms per cubic meter (μg/m^3) in 1966 to 2.3 μg/m^3 in 1980 to about 1 μg/m^3 in 2000. This translates to decreases in BC by as much as 90 percent since 1966. (The data after 2000 are based on a small number of monitors and may not be representative of statewide concentrations. Please see *Technical Considerations* for a discussion of the data presented.)

The graph also shows, concurrent with this large decrease in BC concentrations, that distillate fuel oil consumption increased by about 3-fold (from 0.2 to 0.6 quads; a quad is 10^{15} British thermal units or BTU) over the past 45 years. Since 1960, the majority of distillate fuel oil has been increasingly consumed in the transportation sector, and since 1970, the majority of transportation distillate has been consumed by on-road diesel vehicles. Taxable diesel consumption increased from 0.067 quads in 1967 to 0.358 quads in 2000, or about a factor of 5.

Why is this indicator important?

Black carbon—tiny soot particles released into the atmosphere by burning fuels—has been linked to adverse health and environmental impacts through decades of scientific research. BC has more recently been recognized as one of the major short-lived contributors to climate change. It plays an important role in affecting climate because it absorbs solar radiation, influences cloud processes (thus affecting precipitation and cloudiness), and alters the melting of snow and ice cover. While the direct absorption of solar radiation by BC results in warming, the indirect feedbacks resulting from the interaction between BC (as well as other aerosols) and clouds, and subsequent temperature responses may have both warming and cooling effects. In contrast to the direct BC effect, the net climate forcing due to these indirect cloud feedbacks is highly uncertain (Bond et al., 2013; Ramanathan et al., 2013).

Based on recent estimates of its radiative forcing, BC is the second leading cause of global warming, after carbon dioxide (CO_2). (Radiative forcing is a measure of the climate impact of an atmospheric constituent. It represents the degree by which the constituent can alter the balance of incoming and outgoing energy in the earth-atmosphere system. Radiative forcing values reflect changes relative to pre-industrial conditions defined at 1750 and are expressed in watts per square meter.)

Unlike CO_2 and other long-lived greenhouse gases, BC has a very short atmospheric lifetime—BC particles are removed from the atmosphere via precipitation and by contact with surfaces after a few days to weeks (an average of about a week). As a result, BC concentrations are strongly correlated to regional emission sources, resulting in climate effects that are more regional and seasonal than the more uniform effects of long-lived, well-mixed greenhouse gases.

The direct and snow/ice albedo effects of BC are widely understood to lead to climate warming. BC deposited on snow and ice darkens the surface and decreases reflectivity (albedo), thereby increasing absorption and accelerating melting. California is especially sensitive to the radiative effects of BC. Summer water supplies in California rely predominantly on runoff from mountain snow packs located within the State as well as from the Rocky Mountains via the Colorado River.

Emission reductions can have immediate benefits for climate and health. Thus, BC emission reductions are a mitigation strategy that reduces climate warming from human activities in the short term and slows the rate of climate change. Mitigation actions for BC produce different climate results depending on the region, season, and sources in the area where the emissions reductions occur (Ramanathan et al., 2013).

Air pollution regulations to protect against the adverse health effects of particulate matter (PM2.5 and PM10) have led to the significant reductions in emissions of BC. These reductions, mostly from diesel engines since the 1980s, have also produced a measurable mitigation of anthropogenic global warming—estimated to be equivalent to eliminating 21 million metric tons (MMT) of CO_2 emissions annually. When all sources of BC emissions from diesel fuel combustion are considered, including farming and construction equipment, trains, and ships, the reduction in CO_2-equivalent emissions is estimated to be 50 MMT per year over the past 20 years.

What factors influence this indicator?

The major sources of BC in California are diesel-burning mobile sources, residential wood burning in fireplaces and heaters, agricultural burning, and wildfires. These sources and the ambient concentrations of BC vary geographically and temporally. Some seasonal patterns in emissions are expected for some of the source categories. A strong annual cycle is apparent, with maximum values occurring during the winter, and minimum values in the summer. This seasonality continued over several decades, and is related to meteorological conditions. There is also a strong weekly cycle with the lowest levels on weekends and highest during mid-week, suggesting that the transportation sector is the predominant source.

Despite the increasing trend in diesel fuel consumption—which could have resulted in increased BC emissions—BC concentrations declined significantly. This is due in large part to California's air quality regulations for diesel engines, beginning with the introduction of the first smoke reduction standards in the 1970s. Other regulations include requirements leading to the broad use of diesel particle filters; a control equipment verification program; rules limiting truck and bus idling; and the California Air Resources Board (CARB) Diesel Risk Reduction Plan to reduce diesel particulate matter emissions another 85 percent from 2000 levels by 2020. Regulation of emissions from other sources in the transport sector, from industrial sources, and by decreasing burning of biomass are also contributors to the steady decrease in BC concentrations in California.

Wildfires contribute to California's BC emissions on an episodic basis. Spikes in BC concentrations in 1999 and 2008 correspond to major California forest fire years. The size, frequency, severity, and duration of fires are influenced by climate, and California's fire season appears to be starting sooner and lasting longer (see the *Large Wildfires* indicator, page 137). As the frequency and size of forest fires are projected to increase, perhaps several-fold, by the end of the century, BC emissions from this source may likewise increase in the future.

Technical Considerations:

Data Characteristics

Because they reside in the atmosphere for a short time and their strong dependence on very local sources, particles exhibit high spatial and temporal variation, requiring frequent measurements at numerous sites to reliably track trends. However, few extensive records of particle concentrations are available. One of the first measures of particulate matter pollution used by regulatory agencies, the coefficient of haze (COH), was determined to be a strong proxy for BC, based on collocated field measurements of BC and COH. BC concentrations were inferred from COH data based on a relationship determined from statistical analyses (see Chapter 2.0 of Ramanathan et al., 2013).

Statewide average BC concentrations were computed separately using the data from CARB and the U.S. Environmental Protection Agency (EPA).

Strengths and Limitations of the Data

The U.S. EPA data lacked many of the sites contained in the CARB data set. Where both datasets overlap, agreement is very good. Both sources of data do not have sites located in the Los Angeles-San Bernardino region, precluding an evaluation of BC trends for this key urban area. Thus, the statewide average BC concentrations shown in the graph are likely biased low due to the exclusion of data from this region.

Data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) monitoring sites in California were compared with the COH data. The IMPROVE network uses thermal optical reflectance techniques to provide a record of elemental carbon that is typically used as a surrogate for BC. COH monitors were located predominantly in urban areas at low altitude, while most IMPROVE sites are in rural areas. Trends in the annual average measured BC concentrations from the IMPROVE network were found to be consistent with the trends based on COH records.

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ACIDIFICATION OF COASTAL WATERS (NEW)

TYPE II INDICATOR

Carbon dioxide (CO_2) is considered to be the largest and most important anthropogenic driver of climate change (see *Atmospheric Greenhouse Gases indicator,* page 19). CO_2 is continuously exchanged between land, the atmosphere, and the ocean through physical, chemical, and biological processes (IPCC, 2007c). The ocean absorbs nearly one quarter of the CO_2 released into the atmosphere by human activities every year. As atmospheric CO_2 levels increase, so do CO_2 levels in the ocean, changing the chemistry of seawater—a process called ocean acidification. Ocean acidification has been referred to as the "other CO_2 problem" because it is, like climate change, the result of increasing levels of CO_2 in the atmosphere (Doney, Fabry et al., 2009). The pH (a measure of acidity) of ocean surface waters has already decreased by about 0.1 unit since the beginning of the Industrial Revolution, from 8.2 to 8.1 (NOAA, 2010).

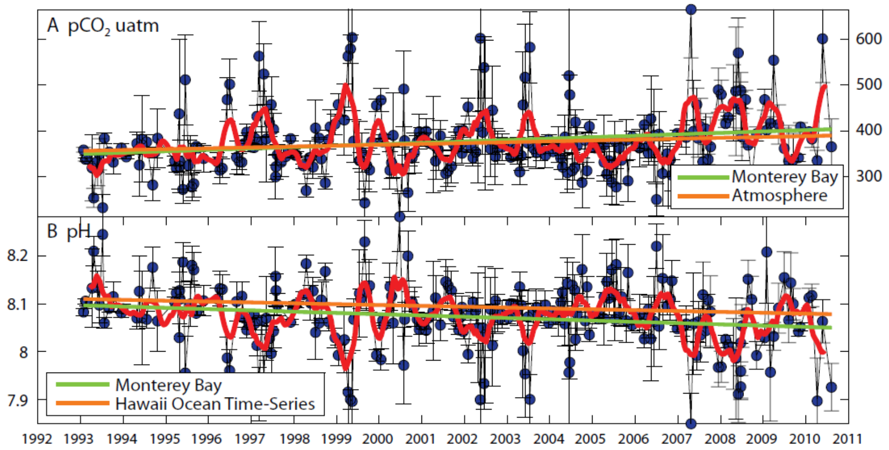
Levels of CO_2 in seawater are governed by both chemical and biologically-mediated reactions (photosynthesis, respiration, and calcium carbonate precipitation and dissolution). The air-sea exchange of CO_2 is determined largely by the difference in the partial pressure of CO_2 (pCO_2) between the atmosphere and the ocean. When seawater pCO_2 is lower than the atmospheric pCO_2, seawater takes up CO_2 from the overlying air; when it is greater than the atmospheric pCO_2, CO_2 is emitted to the air (Takahashi et al., 2010). CO_2 in seawater reacts with water to form carbonic acid (H_2CO_3), most of which dissociates into a hydrogen ion (H^+) and a bicarbonate ion (HCO_3^-); some of the H^+ subsequently reacts with carbonate (CO_3^{-2}) to form more HCO_3^- ions. The net result of adding CO_2 to seawater is an increase in H^+—which increases seawater acidity and lowers seawater pH—and in HCO_3^-, along with a reduction in CO_3^{-2} (IPCC, 2007c). H^+ concentration (acidity) is measured on the pH scale ($pH = -\log[H^+]$), which is an inverse scale, so increases in H^+ correspond to decreases in pH. Thus, the lower the pH, the more acidic the solution. It is notable that the increase in oceanic CO_2 over the last two decades is consistent with the atmospheric increase. The rise in seawater pCO_2 has been accompanied by declining pH (NOAA, 2010).

In the presence of sunlight, phytoplankton in surface waters convert CO_2 to organic matter through photosynthesis. A fraction of the organic matter sinks below the surface where it is decomposed, causing vertical variations in the concentrations of inorganic carbon species (CO_2, HCO_3^-, and CO_3^{-2}) and pH. Another important biological process is the production of calcium carbonate by marine life (mostly in the form of the minerals calcite and aragonite) to serve as skeletons or hard protective structures (NAS, 2010).

The vertical variation of pH in the ocean has been found to vary with geographic location, particularly as a function of latitude. pH also varies on time scales ranging from daily to inter-annual or longer, reflecting changes in biological processes that affect H^+ concentration, as well as chemical and physical processes that may change the H^+ content of a water mass or large-scale circulation patterns. For example, cyclical seasonal variations occur, as the intensity of biological processes varies with season, and the solubility of CO_2 varies with temperature (NAS, 2010). Changes associated with large-scale climate oscillations such as El Niño and the Pacific Decadal Oscillation can alter the oceanic CO_2 sink/source conditions through seawater temperature changes as well as through ecosystem variations that occur via complex physical-biological interactions (Chavez et al., 2007).

In coastal waters, the processes affecting acidification are much more complex than in the open ocean and deep waters due to the influence of freshwater and atmospheric inputs, organic matter and algal nutrients inputs from land, and processes in the underlying sediment. Acidification can be mitigated or intensified by high rates of production or respiration, respectively, in coastal waters that may be fueled by inputs of nutrients or organic matter from land (NAS, 2010).

CO_2 and acidity measurements at Monterey Bay



Source: MBARI, 2011

Upper panel, A: Partial pressure of CO2 in microatmospheres
Lower panel, B: Acidity (pH)

Monterey Bay is perhaps the only place on the West Coast where two carbon parameters have been sampled regularly since 1993 (MBARI, 2011). These data support the hypothesis that acidification is occurring along the West Coast (NOAA, 2010). Levels of pCO_2 at the sea surface (upper panel of graph, measured in microatmospheres or μatm) have increased, while exhibiting considerable variability. The increase in seawater pCO_2 has been slightly higher than the increase in atmospheric pCO_2. During the same time period, pH has decreased (bottom panel of graph). The decrease in pH (and hence the increase in acidity) in Monterey Bay waters has been greater than that in the open ocean near Hawaii (MBARI, 2011).

While the gradual process of ocean acidification has long been recognized, the ecological implications of such chemical changes have only recently been examined (Doney et al., 2009; NAS, 2010; NOAA, 2010). The best-documented and mostly widely observed biological effect is decreased calcification rates in a wide range of shell-forming organisms, including plankton, mollusks, and corals. There is also evidence that the changes in ocean water chemistry—including secondary chemical reactions that alter various forms of trace elements and nutrients—affect a range of biological processes in marine organisms, including the fixation and respiration of CO_2, regulation of internal pH, and uptake of nutrients for growth. The indirect effects of acidification, in tandem with changes in oxygen, temperature, and other factors that are predicted to change, are likely to impact nearly every species in marine food webs to some extent through predator-prey interactions, increased prevalence of invasive species, changes in pathogen distributions, and alterations of physical ecosystem structure. Species responses and degrees of sensitivity will vary considerably. Similarly, certain ecosystem types are expected to be more vulnerable than others.

Along the West Coast, ocean acidification adds to the already naturally high levels of CO_2 in upwelled waters. Upwelling is the wind-driven movement of deep, cool, and CO_2- and nutrient-rich ocean water to the surface, replacing the warmer, usually nutrient-depleted surface water. Upwelled waters also characteristically have lower saturation states for the major carbonate minerals (aragonite and calcite) than surface waters, making it more difficult for species with calcium carbonate shells or skeletons to synthesize or maintain their shells. Many economically and ecologically important West Coast species are expected to show direct responses to acidification; bivalves, for example, are economically valuable, while also serving an ecological role in providing limiting substrate for other species. Recent observations indicate that bivalve shellfish hatcheries on both the West and East Coasts are experiencing a decline in production. Other stressors already impact coastal ecosystems—including fishing pressures, input of chemical contaminants, exotic and invasive species—and additional pressures are likely to occur as a result of the overarching effects of climate change (NOAA, 2010).

Despite the central importance of data on long-term changes in the ocean's carbon system, coordinated observing networks in the U.S. coastal and estuarine waters did not exist until recently. The National Oceanic and Atmospheric Administration (NOAA) has launched an observational program to monitor the magnitude and variability of decreased ocean pH and calcium carbonate saturation states as well as their impacts on marine ecosystems. Key physical, chemical, and biological parameters are being measured through ship-based and moored observational platforms to support efforts to predict how marine ecosystems will respond and to develop management strategies for adapting to the consequences of ocean acidification. Efforts in California coastal waters include moorings with CO_2 and pH sensors, regular measurements of inorganic carbon species on CalCOFI and MBARI cruises, surface measurements of CO_2 and pH from ships of opportunity, and shore-based observations of carbon chemistry in nearshore waters (see http://pmel.noaa.gov/co2/story/Observations+and+Data, http://www.mbari.org/moos/, and http://omegas.science.oregonstate.edu/). These monitoring efforts are carried out in collaboration with a wide range of national, regional and international partners. Temporal and spatial trends in pH and calcium carbonate saturation states for coastal areas will provide good indicators of the extent of the acidification in California's coastal ecosystems (NOAA, 2010).

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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. Globally, widespread observations of temperature increases and changes in other climate variables provide unequivocal evidence that the Earth’s climate is warming. While natural internal processes cause variations in global mean temperature for relatively short periods, a large portion of the observed temperature trend is due to external factors. 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 (IPCC, 2007e).

INDICATORS: CHANGES IN CLIMATE

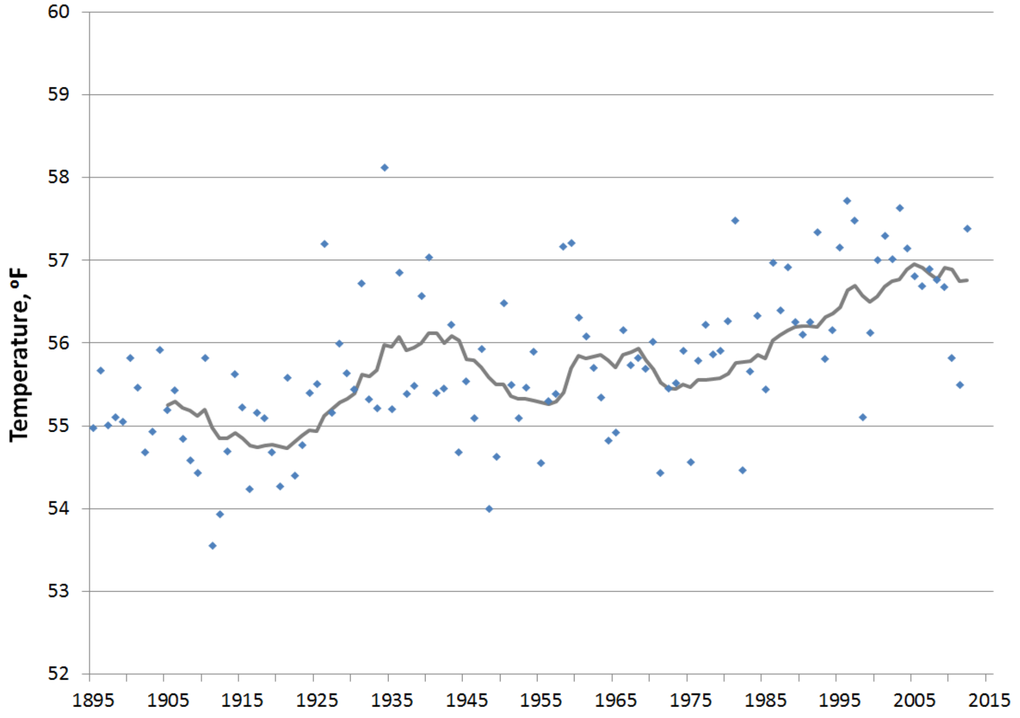
Annual air temperature *(updated)*
Extreme heat events *(updated)*
Winter chill *(updated information)*
Freezing level elevation *(new)*
Annual precipitation *(updated)*

Reference:
IPCC (2007e). *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

ANNUAL AIR TEMPERATURE (UPDATED)

Air temperatures have increased over the past century.

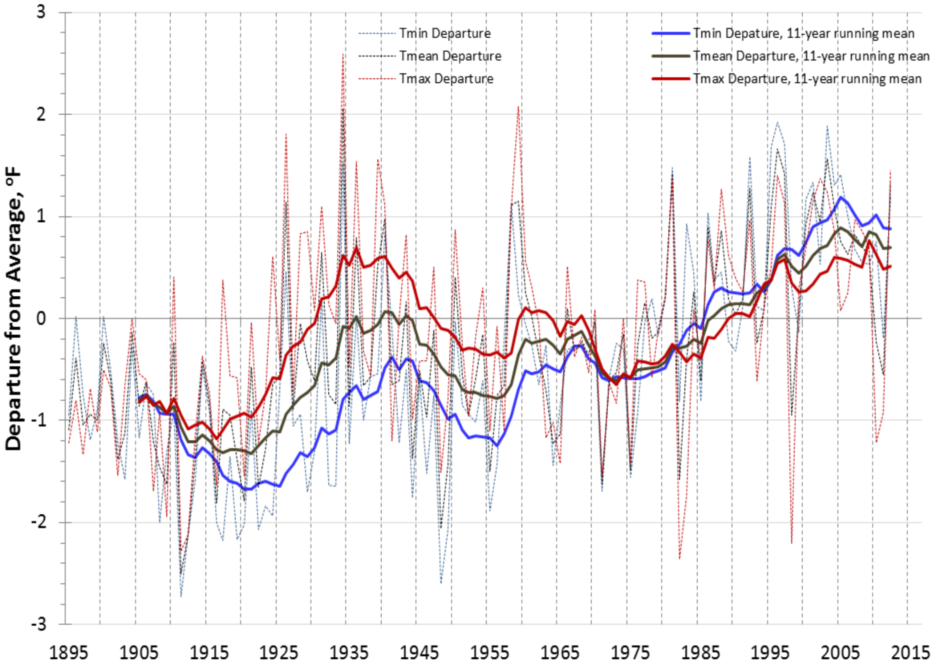
Statewide Annual Average Temperatures, 1895-2012



Bold line is the 11-year running average.

Source: WRCC, 2013

Statewide Annual Temperature: Departure from Average (1895-2012)



Source: WRCC, 2013

Temperature Departures: Definition of terms used

Average is the long-term average temperature based on data from 1949 to 2005.

Departure is the difference between the long-term average and value for the period of interest. Positive values are above, and negative values are below, the long-term average.

Maximum and minimum temperature is an average of the maximum or minimum temperature values for a given length of time.

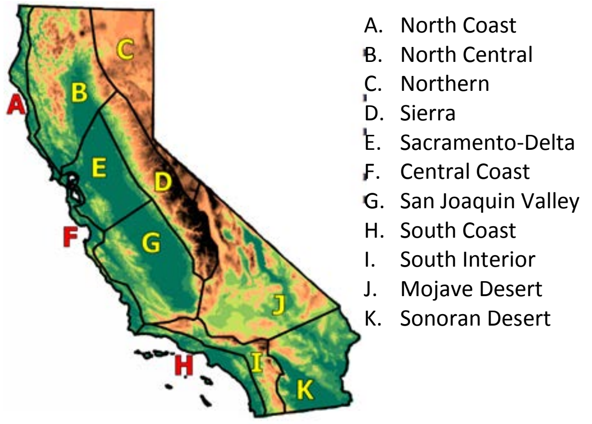
Mean temperature is the simple average of maximum and minimum temperatures, or the sum of maximum + minimum, divided by 2.

What is this indicator showing?
Statewide air temperatures have been warming since 1895 (WRCC, 2012), a trend consistent with that found globally (IPCC, 2007a). The first graph plots actual annual average temperatures for the State. Since 1895, annual average temperatures have increased by about 1.5 degrees Fahrenheit (^{o}F) per century.

The second graph shows "departures" for annual minimum, average (mean) and maximum temperatures each year from a long-term average (the years 1949 to 2005)—i.e., the difference between each year's value and the long-term average. As shown on the graph, minimum, average and maximum temperatures have been increasing since 1895. Minimum temperatures (which generally occur at nighttime) have increased the fastest. Maximum temperatures (which generally occur during the day), by contrast, have increased only slightly since the warm period in the 1930s. Minimum temperatures rose at a rate of 1.99^{o}F per 100 years, maximum temperatures at 1.01°F. It appears that the increasing trend in mean California temperature is driven more by nighttime processes than by daytime processes.

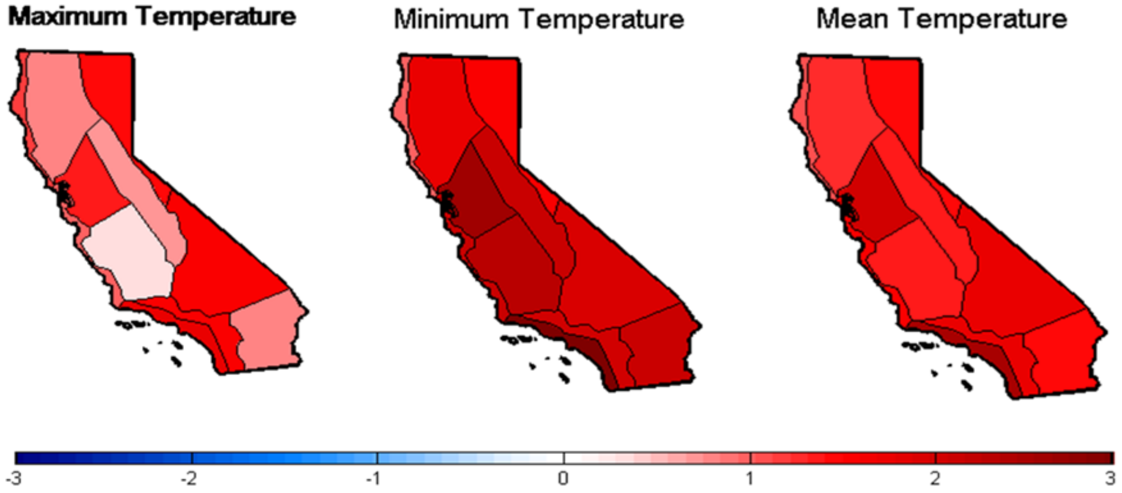
All of California's 11 climate regions (see map, right) show warming trends over the last century, although at varying rates. The increases in minimum temperatures are greater than increases in either mean or maximum temperatures. Changes in maximum temperatures appear to show greater differences among regions.

California's Climate Regions



Source: WRCC, 2012

Annual temperature trends for 11 climate regions in California
Linear Trend (1895-2007), in ^{o}F per century



Source: WRCC. 2008

Why is this indicator important?

Temperature is a basic physical factor that affects many natural and human activities. Increasing temperatures can have a wide range of impacts on, for example, agriculture, coastal areas, wildfires, water supplies, ecosystems and human health. Understanding observed temperature trends is important for refining future climate projections for climate sensitive sectors and natural resources within the state (Cordero et al., 2011).

What factors influence this indicator?

Temperatures 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 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.

Globally, the increase in the concentration of carbon dioxide and other greenhouse gases in the Earth’s atmosphere since the industrial era in the mid-1700s has been a principal factor causing warming over the past 50 years (USGCRP, 2009). Emissions of these greenhouse gases are intensifying the natural greenhouse effect, causing surface temperatures to rise. Greenhouse gases absorb heat radiated from the Earth’s surface and lower atmosphere, and radiate much of the energy back toward the surface.

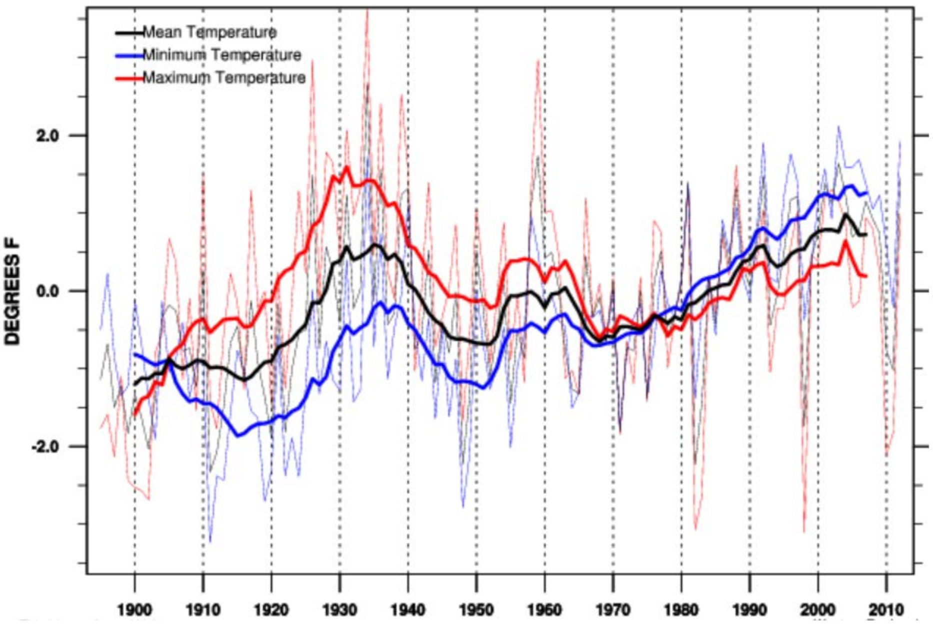
There are local influences on temperatures as well as those that have changed over time, including land surface uses and types, for example, widespread irrigation, urban heat island effects versus rural landscapes. In addition, urbanization of historically rural areas can increase temperature, which is generally known to have a warming effect. This is due in large part to the heat absorbing concrete and asphalt in building materials and roadways.

Regional temperature trends

Sierra Region

The Sierra 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 region 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.

Sierra Region Annual Temperature Departure
(based on 1949-2005 averages)



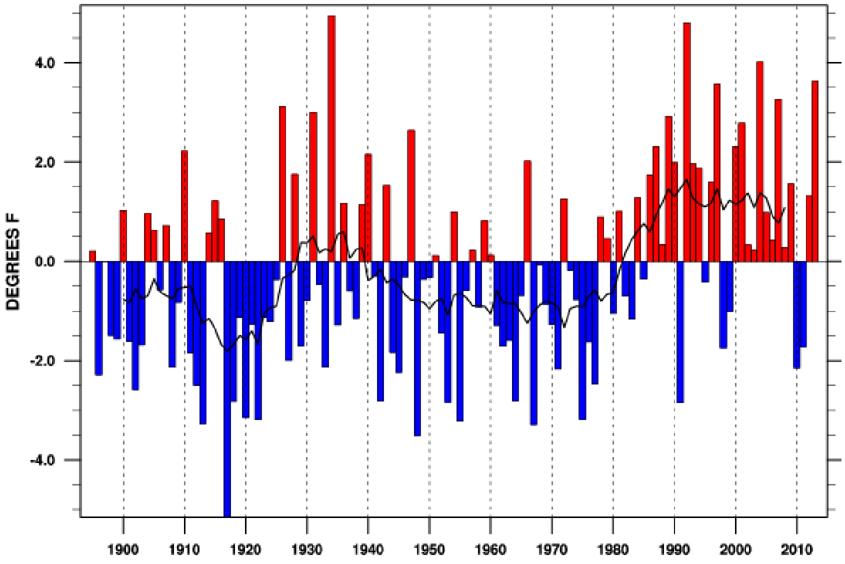
Annual (Jan-Dec) temperature, expressed as departures from average. Red is maximum temperature, blue is minimum temperature, black is mean temperature. Thin lines are annual values. Bold lines are the 11-year running mean.

Source: WRCC, 2013

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.

Of interest is the increase in spring season minimum temperatures (see graph, next page). The increase 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 region 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).

Sierra Region Minimum Temperature Departure:
March to May (based on 1949-2005 averages)



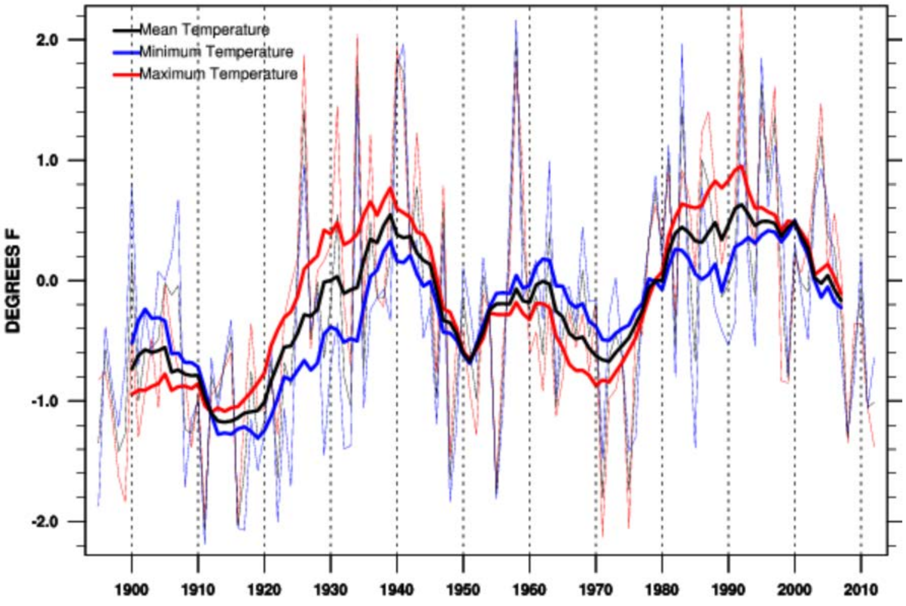
Black line denotes 11-year running mean

Source: WRCC, 2013

Coastal regions

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. Mean annual temperatures (bold black line) of the last two decades are similar to those of the 1930s.

North Coast Region Annual Temperature Departure
(based on 1949-2005 averages)

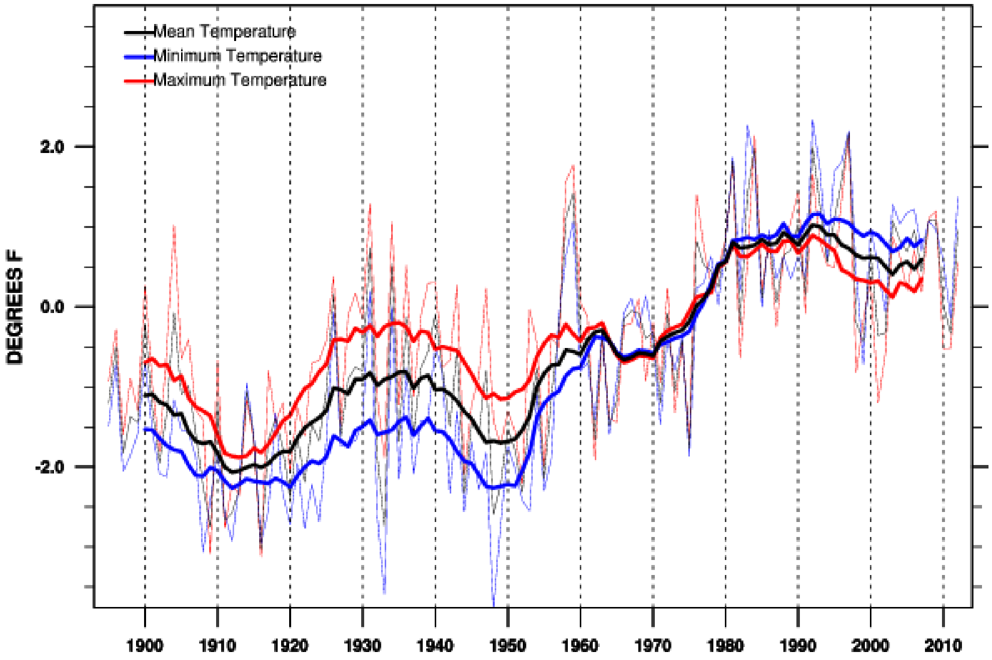


Annual (Jan-Dec) temperature, expressed as departures from average. Red is maximum temperature, blue is minimum temperature, black is mean temperature. Thin lines are annual values. Bold lines are the 11-year running mean.

Source: WRCC, 2013

The South Coast region, on the other hand, has experienced greater warming 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.

South Coast Region Annual Temperature Departure
(based on 1949-2005 averages)



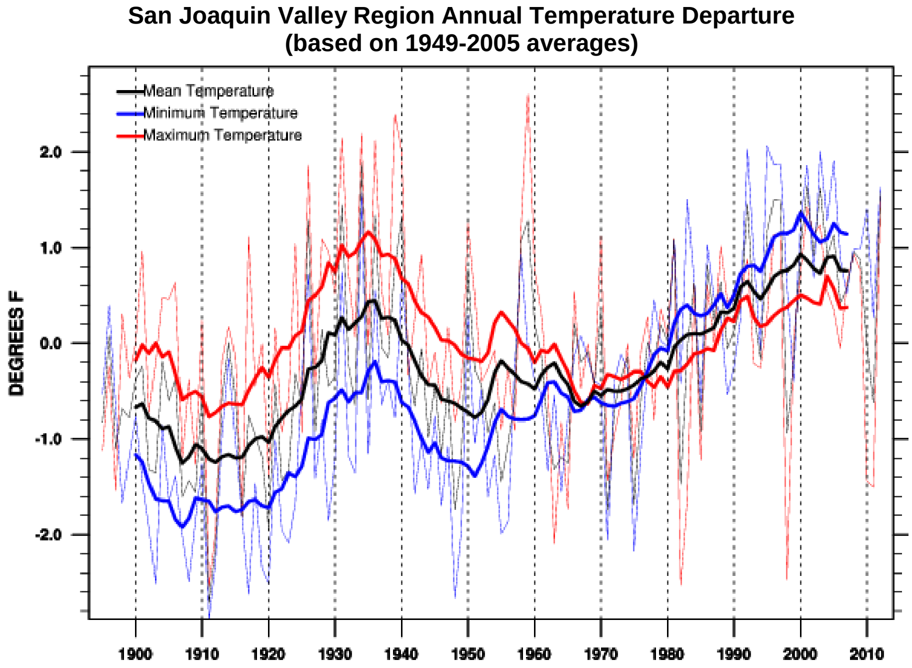
Annual (Jan-Dec) temperature, expressed as departures from average. Red is maximum temperature, blue is minimum temperature, black is mean temperature. Thin lines are annual values. Bold lines are the 11-year running mean.

Source: WRCC, 2013

Despite the overall warming trends, the temperatures for the coasts have decreased in recent years—even leveling over the past quarter century. Attribution of the cause of this cooling or slower warming trend is unclear at this time. Possible influences could be from increased coastal fog or marine stratus clouds. It has also been suggested that coastal cooling trends over the last 30 years are a result of an enhanced sea breeze circulation driven by warming over the interior of the state (Cordero et al., 2011).

San Joaquin Valley

The San Joaquin Valley region shows an increasing temperature trend since the mid-1970s, with minimum temperatures rising faster than maximum temperatures. Research on this region in recent years has investigated the possible role of irrigation on temperature trends (e.g., Christy et al., 2006; Bonfils and Lobell, 2007). However, 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. Urbanization appears to primarily raise minimum temperatures (e.g., LaDochy et al., 2007), while irrigation appears to both cool maximum temperatures and warm minimum temperatures (e.g., Bonfils and Lobell, 2007; Kueppers et al., 2007).



San Joaquin Valley Region Annual Temperature Departure
(based on 1949-2005 averages)

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

Source: WRCC, 2013

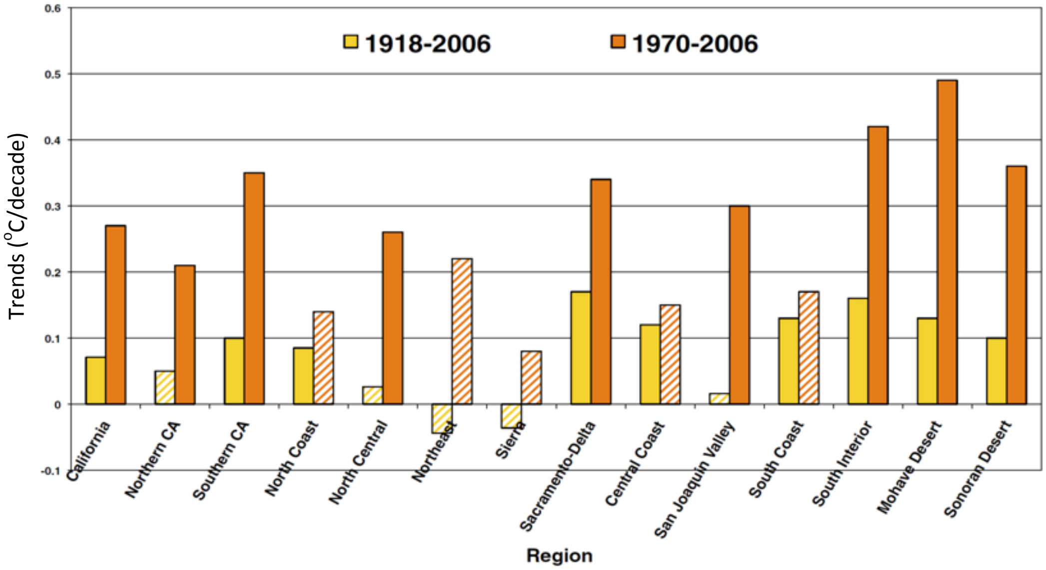
<u>Analysis of temperature trends</u>

A recent analysis of annual temperature data for California over the last 80 years showed distinctly different spatial and temporal patterns in trends of maximum temperatures (Tmax) and minimum temperatures (Tmin) (Cordero et al., 2011). The graphs that follow summarize the findings from this analysis.

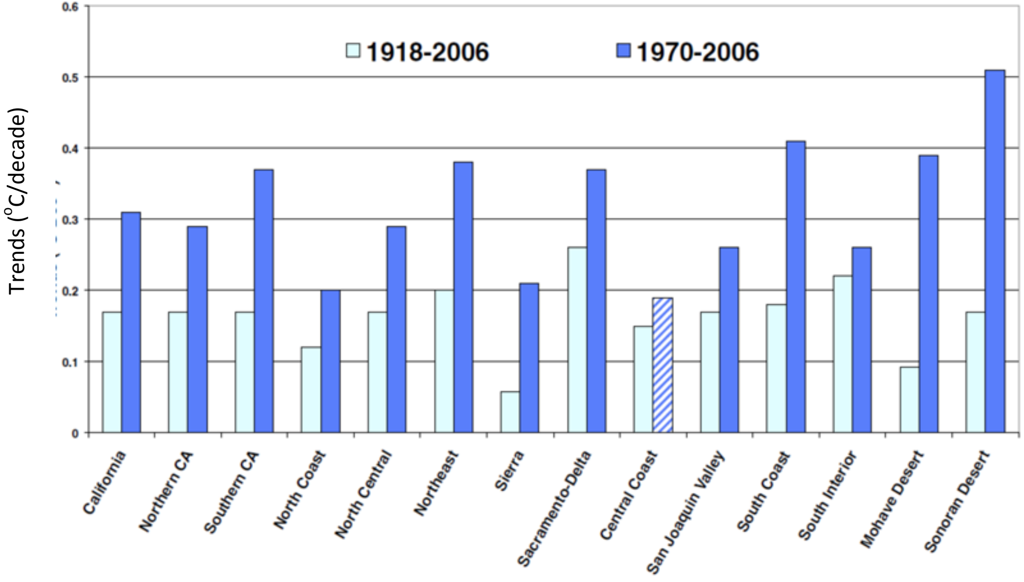
Annual trends for Tmins for each of California's 11 regions showed warming from 1918-2006, with parts of the Central Valley and Southern California showing the greatest warming (0.26^{o}C/decade for the Sacramento-Delta; 0.22^{o}C/decade for the South Interior). The Sierra Nevada (0.06^{o}C/decade) and the Mojave Desert (0.09^{o}C/decade) showed the weakest warming. For Tmax, 7 out of 11 regions exhibited warming, with the strongest warming again found in the Sacramento-Delta (0.17^{o}C/decade) and the southern part of the state (0.10 to 0.16^{o}C/decade).

Trends for two different time periods—1918-2006 and 1970-2006—were also analyzed. The most prominent feature in this comparison was accelerated warming trends for the more recent period (1970-2006). Statewide Tmax trends between 1970-2006 (0.27^{o}C/decade) were more than three times as large as the trend for the earlier period (0.07^{o}C/decade); Tmin trends between 1970-2006 (0.31^{o}C/decade) were almost twice as large as trends between 1918-2006 (0.17^{o}C/decade). The finding that trends for Tmin were larger than Tmax for the entire period, while trends in Tmin were nearly the same as Tmax since 1970, is qualitatively similar to results observed for global temperature.

Statewide and Regional Maximum Temperature Trends



Statewide and Regional Minimum Temperature Trends



Source: Cordero et al., 2011

***Note**: Solid bars are statistically significant (at 95% confidence level); hashed bars are not.*

Although the statewide trends in Tmin and Tmax since 1970 are about the same, there are distinct regional differences, as shown in the graphs above. In the northern part of the state (North Coast, North Central, Northeast regions), the average Tmax trend was 0.20°C/decade, while the average Tmin trend was 0.27°C/decade. In the southern part of the state (South Interior, Mojave Desert, Sonoran Desert regions), the average Tmax trend was 0.41°C/decade while the average Tmin trend was 0.37°C/decade. The difference in warming trends between these northern and southern regions was statistically significant and most pronounced in Tmax. Since 1970, warming Tmin trends were statistically significant in 10 regions, while warming Tmax trends were statistically significant in only 6 out of the 11 regions. Regions that did not observe a statistically significant warming of Tmax (hashed bars) included both coastal and mountain (northeast and Sierra) regions of the state.

Technical Considerations

Data Characteristics

Two data sources are used to create a single value for each temperature variable each month: (1) data for nearly 200 climate stations in the NOAA Cooperative Network within California (from the Western Regional Climate Center database archive of quality controlled data from the National Climatic Data Center); and (2) gridded climate data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al., 1997) acquired from the PRISM group at Oregon State University. PRISM provides complete spatial coverage of the state. Because climate stations are not evenly spaced, the PRISM data are used to provide even and complete coverage across the state. 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 (Abatzoglou et al., 2009).

Strengths and Limitations of the Data

The datasets used in this work are 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., 2009).

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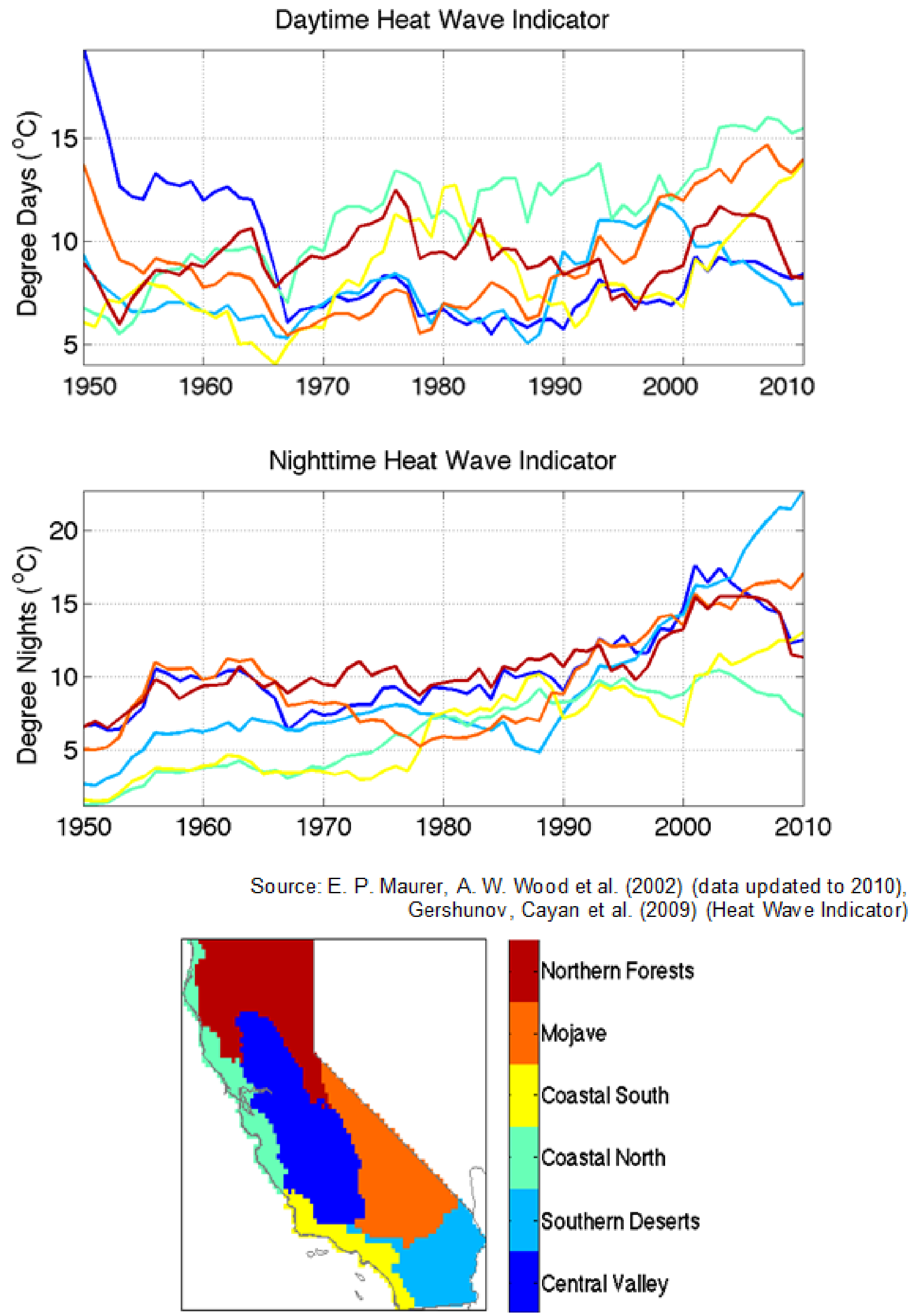
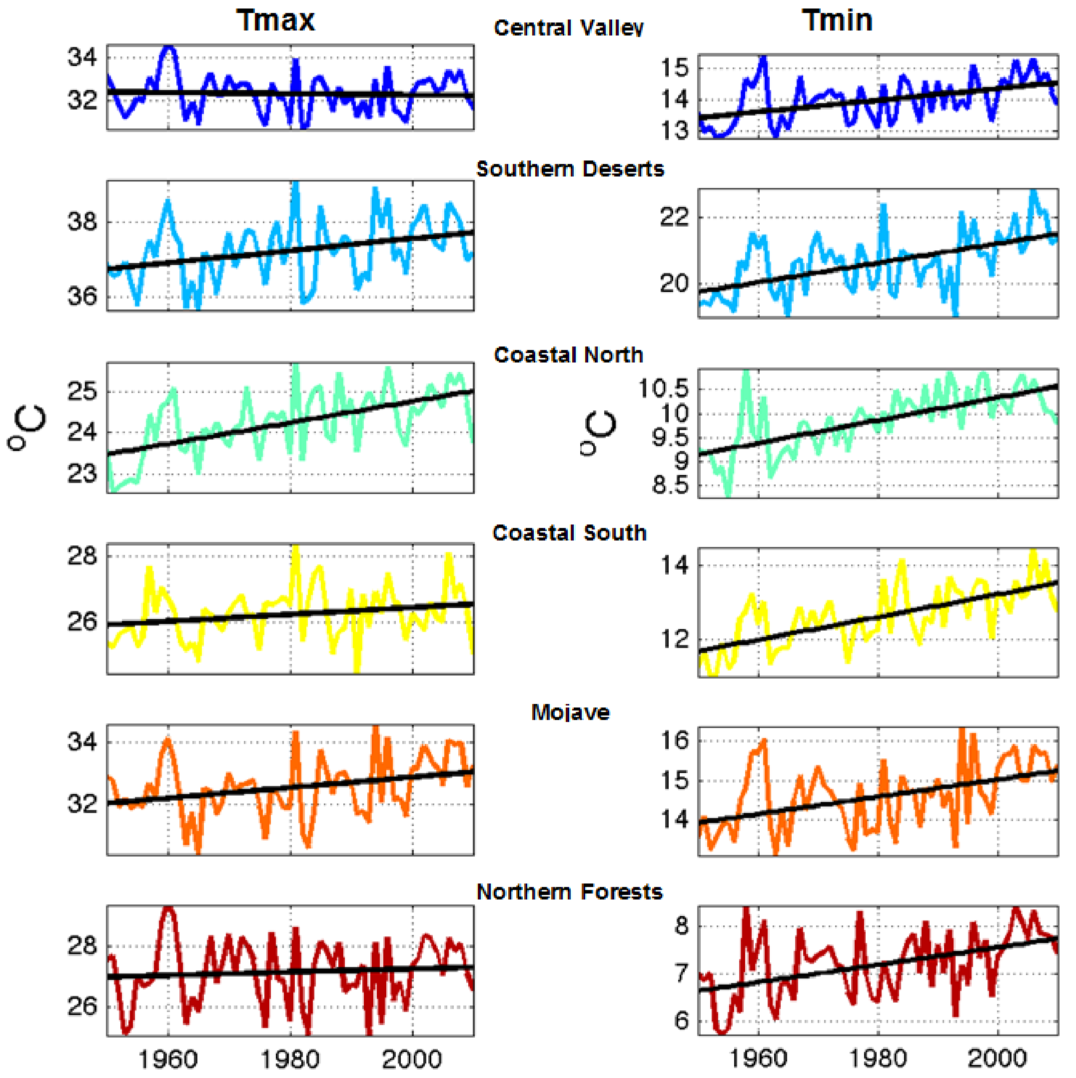
EXTREME HEAT EVENTS (UPDATED)

Summertime temperature extremes are increasing across all climate regions, in California, with sharper increases seen at night; the largest increases are observed for coastal regions.



Source: E. P. Maurer, A. W. Wood et al. (2002) (data updated to 2010), Gershunov, Cayan et al. (2009) (Heat Wave Indicator)



Maximum and Minimum Temperatures, by region
(June to August)

Source: Maurer, Wood et al. (2002 (data updated to 2010)
http:www.engr.scu.edu/~emaurer/gridded_obs/index_gridded_obs.html

What is the indicator showing?
The first set of graphs show regional heat wave indicators, which reflect daytime (top graph) and nighttime (bottom graph) summertime heat wave activity for each of six climate regions in California (see map). To derive the heat wave indicator, historical temperatures are evaluated at each location (grid box) and a local threshold is calculated as the 95th percentile over the reference period 1950-1999. By definition, daytime or nighttime heat waves occur when the minimum temperature (Tmin) (for the

nighttime heat wave indicator) or the maximum temperature (Tmax) (for the daytime heat wave indicator) for a given day exceeds that local temperature threshold. For each location, the heat wave indicator is derived as the sum of exceedances over the 95th percentile threshold from June 1 through August 31st of each year. The summation of these total exceedances for all of the locations within each 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. In the graphs, the heat wave indicators are normalized by the regional area and smoothed for clarity.

There is strong evidence of multi-decadal variability in summertime daytime heat waves for all regions, with a tendency toward increased heat wave activity in the Coastal North and Mojave regions and a decreasing trend for the Central Valley. Nighttime heat waves, however, are associated with a long-term linear trend that is apparent in all climate regions. The increase in nighttime heat wave activity is associated with an increase in humidity (Gershunov et al., 2009), which impedes radiative cooling and helps to maintain high temperatures throughout the night.

As shown in the second set of graphs, summertime (June-August) maximum (Tmax) and minimum (Tmin) temperatures have increased between 1950 and 2010 for each of the six climate regions. The map of California climate regions is based on a space-time analysis of temperature extremes (see Richman and Lamb, 1985; Comrie and Glenn, 1998; Guirguis and Avissar, 2008 for methodology). Tmax reflects the hottest daytime temperatures, while Tmin reflects the coolest nighttime temperatures.

Tmax increased for all regions except the Central Valley. The largest increase is observed for the Coastal North, which saw an increase of 0.26°C per decade, or 1.57°C over the 61-year record. The desert regions (Mojave and Southern Deserts) saw the second largest increase in Tmax with a 0.16°C increase (Southern Deserts) and a 0.17°C increase (Mojave) per decade, or 1°C over the 61-year period. Tmax increased in the Coastal South by 0.10°C per decade, or 0.64°C over the record. For the Northern Forests, Tmax increased by 0.05°C per decade or 0.32°C over the 61-year record. The Central Valley saw a slight decrease of 0.03°C per decade, or 0.17°C over the analysis period.

Tmin increased for all regions, and this trend was generally larger than the trend in Tmax (except for the Coastal North, where the Tmax trend was larger). The largest increase in summertime minimum temperatures was seen in the southern parts of California. The Coastal South saw the biggest trend, with Tmin increasing by 0.31°C per decade, or 1.89°C over the record. The Southern Deserts saw the second largest increase in Tmin with an increase of 0.29°C over the decade, or 1.78°C over the 61-year period. The Coastal North observed the third largest increase of 0.24°C per decade, or 1.45°C over the record. The Mojave increased by 0.22°C per decade, or 1.33°C in all. The Central Valley and Northern Coasts increased by 0.18°C per decade or 1.1°C over the 61-year record.

Why is this indicator important?

Increases in both minimum and maximum temperatures, particularly during the summer, are expected 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; less information exists on temperature-related illnesses (CCSP, 2008; see *Heat-related mortality and morbidity* indicator, page 124). The impacts of extreme heat events are mediated by factors affecting the vulnerability, resiliency and capacity of a system for adaptation. Hence, tracking trends in the occurrence and magnitude of extreme heat events will help in efforts to plan for, and prepare against, their potential adverse impacts.

It is important to evaluate daytime and nighttime temperatures separately. Humidity increases the health burden of heat waves because people living in the arid and semi-arid climates of California are acclimatized and have adapted to traditionally dry daytime heat and efficient nighttime surface radiative cooling. 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. Temperatures in urban areas can also be affected by the urban heat island effect due to land surface modification and other human activities. However, rural locations see comparable warming and all regions of California are affected. This suggests that urbanization and land use does not explain the changes observed in California. The accelerating increase in California heat wave activity is consistent with global climate change.

The increase in nighttime heat wave activity indicates that heat waves are becoming more humid. Water vapor is the most abundant and important greenhouse gas in the atmosphere. However, human activities have little direct influence on the amount of atmospheric water vapor (IPCC, 2007b). Water vapor absorbs longwave terrestrial radiation and impedes radiative cooling. Therefore, there is less nighttime respite from heat when humidity is high. Moreover, humid heat waves tend to last longer due to the stronger coupling of maximum and minimum temperatures during humid heat waves (Gershunov et al., 2009).

Technical Considerations

Data Characteristics

The minimum and maximum temperature data are gridded observations described in Maurer et al. (2002). This dataset aggregates station observations and interpolates them to a 1/8-degree grid. The station data (approximately one station per 1000 square kilometers) are from the National Climatic Data Center (NCDC, 2007). The NCDC 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 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 station 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. Station coverage is not uniformly distributed geographically and coverage can be quite sparse in mountainous regions such as the Sierra Nevada, therefore there is a bias towards populated areas and lower elevations. Elevation is accounted for in the interpolation; however, choice of interpolation scheme can affect correlation and bias with respect to point measurements. Recorded temperatures in urban areas can also be affected by the urban heat island effect due to land surface modification and other human activities.

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The reported analyses were supported by the University Corporation for Atmospheric Research under the Postdocs Applying Climate Expertise (PACE) fellowship and by the Award Number RC1ES019073 (Principal Investigator: H.G. Margolis) from the National Institute of Environmental Health Sciences. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institute of Environmental Health Sciences or the National Institutes of Health.

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WINTER CHILL (UPDATED INFORMATION)

Chill hours have been decreasing over the past half century.

> *Winter chill is a period of cold temperatures that is required for fruit trees to produce flowers and fruit. The 2009 climate change indicators report quantified winter chill in agricultural regions using a metric developed in the 1930s and 1940s. While this metric provides a useful rule of thumb for California growers, recent studies suggest that it may not be an accurate indicator of winter chill for California's Central Valley, especially under future climate conditions.*

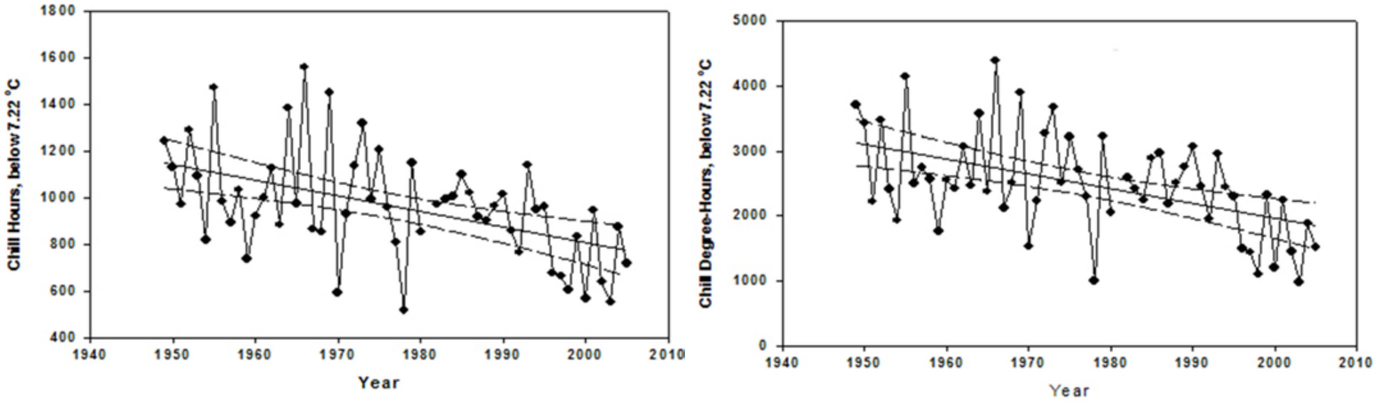
Winter chill models are tools used to understand and manage the interannual variation in the time at which tree crops complete their dormancy. Luedeling et al. (2009a, 2009b, and 2009c) have compared projected winter chill using the "Chilling Hours Model," the "Dynamic Model," and others for expected climate scenarios in California. All models predicted substantial decreases in winter chill at all sites, to varying extents.

The influence of temperature on the biological processes underlying the breaking of dormancy—and the processes themselves—are poorly understood. It is known, however, that not all "chill" is effective. When chill hours alternate with temperatures above 45^{o}F—which is common in California—a canceling effect can occur. The Chilling Hours Model, which simply counts the number of winter hours when temperatures are below 45^{o}F or 7.22^{o}C (as was done to derive the values in the 2009 indicator, next page) does not account for this. The Dynamic Model reflects a more biologically based theoretical framework, incorporating temperature fluctuations in calculating "chill portions" (see Luedeling et al., 2009b for details).

One study using weather data and several greenhouse gas emissions scenarios throughout California's Central Valley projected Chill Portions and Chilling Hours to decrease by 14%-21% and 29%-39%, respectively, between 1950 and 2050 (Luedeling et al., 2009b). Both the models projected climatic conditions by the middle to the end of the 21st century that will no longer support some of the main tree crops currently grown in California, with the Chilling Hours Model projecting greater changes. For California growers, tree crops may tolerate a 20% decline in winter chill but are unlikely to be able to adapt to losses of more than half of current winter chill. The tree crop industry will likely need to develop agricultural adaptation measures (e.g., by growing low-chill varieties) to cope with these projected changes. For some crops, production might no longer be possible (Luedeling et al., 2009a).

The discussion of the winter chill indicator from the 2009 report is reproduced below. *Updated values for winter chill at the location below are not available to OEHHA at this time.*

Winter Chill in Orland, CA



Source: Baldocchi and Wong, 2008

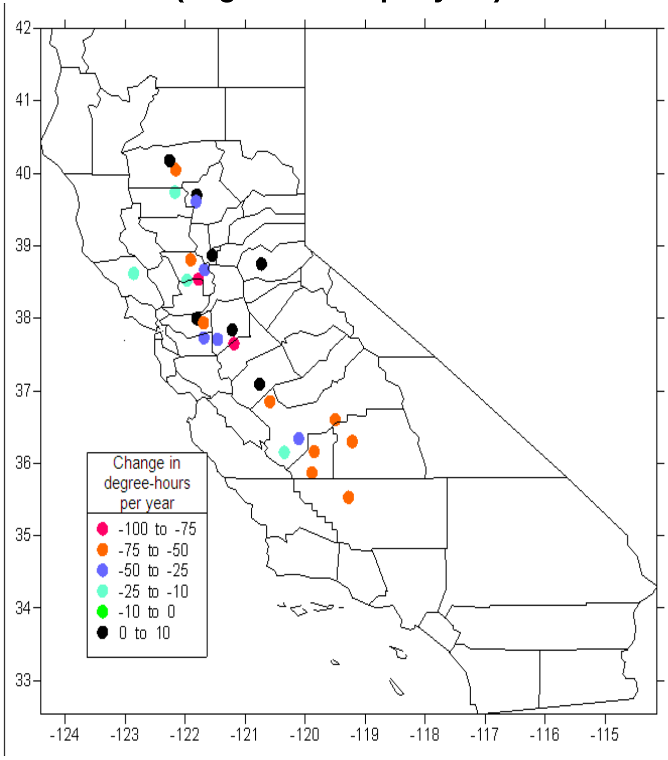
Regression lines (solid) with confidence intervals (dashed lines) are shown.

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°C (45°F), a threshold temperature for dormancy; and, (2) the summation of this number of hours multiplied by the number of degrees tha temperature is below 7.22°C.

The same analysis was repeated on data for other climate stations across the fruit growing valleys of California (see map on the right). Most sites are experiencing

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



Source: Baldocchi and Wong, 2008

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.

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 Orland data are from 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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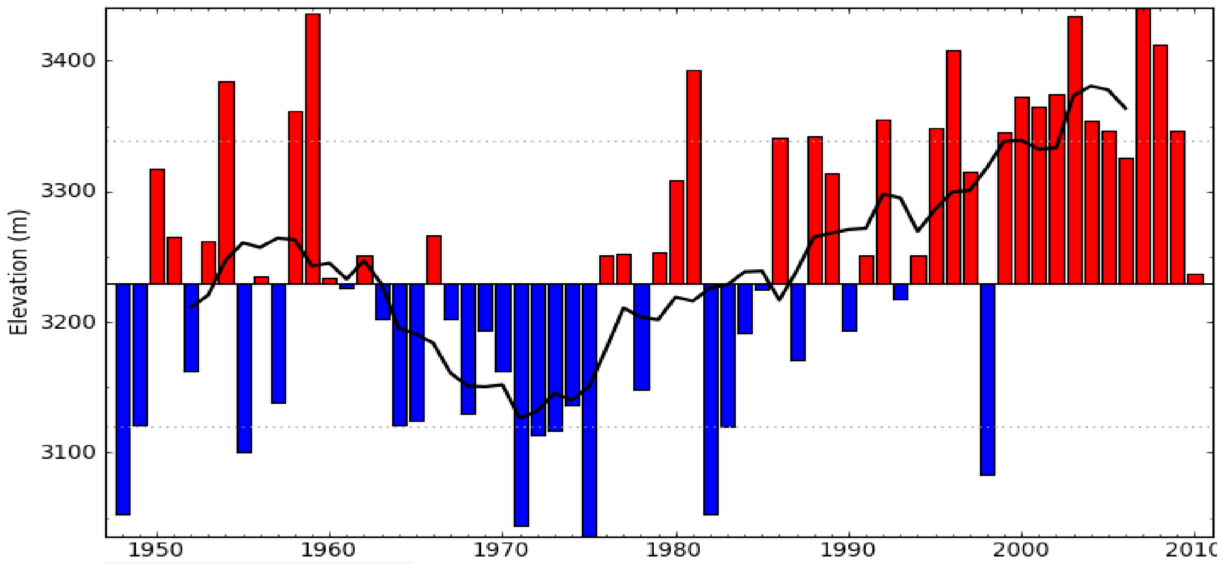
FREEZING LEVEL ELEVATION (NEW)

Freezing level elevation—that is, the altitude in the atmosphere at which temperatures drop below freezing (0^{o}C or 32^{o}F)—has been increasing with time.

Freezing Level Elevation over Lake Tahoe (Annual average)



Black line is 9-year average.

Source: WRCC, 2011

What is the indicator showing?

Away from surface influences, the temperature of the atmosphere decreases with elevation. Everywhere on earth, including over tropical jungles and the major deserts, at sufficient altitude freezing temperatures (0^{o}C or 32^{o}F) occur (the "freezing level"). This phenomenon is visually evident from the famous snows of Mount Kilimanjaro at 3 degrees S latitude in Africa.

The graph shows that the annual freezing level at Lake Tahoe has risen by about 150 meters (around 500 feet) over the past 20 years. During the past decade, freezing levels have been above the 63-year average of 3220 meters, indicating warmer conditions at higher elevations.

Why is this indicator important?

Freezing level elevation is an important parameter globally because it is proportional to (and somewhat lower than) the approximate position of permanent ice and snow on the surface, and thus constitutes an important indicator of climate variability and change (Diaz et al., 2003). Especially in mountainous environments, freezing level is important for hydrology and biology, and often has consequences for transportation, recreation, and other human concerns. The freezing level affects: a) the elevation at which the transition from rain to snow takes place; b) the temperature of the soil surface onto which the first autumn snow lands; c) the evolution of snowpack, density, depth and internal snowpack structure during winter; d) direct loss of snowpack (via sublimation) to the atmosphere in winter; e) the readiness to melt when spring temperatures arrive; and f) the evolution of the melt season.

Freezing level also affects ecological function through biological growth rates (both plants and animals) at different elevations. At temperatures below freezing, many insects, animals and plants cannot grow or function, and have no access to liquid water.

Icing becomes a roadway hazard on mountain passes, and airplane icing causes drastic reduction in lift. Skiing and other outdoor recreation can be sensitive to snow conditions or whether snow is present or not. Flood potential is highly dependent on whether precipitation arrives at the surface as liquid or solid. Falling snow can resist melting down to the ”snow level,” which can be a few hundred to as much as a thousand feet below the freezing level.

What factors influence this indicator?

Two main factors affect the freezing level. The first is the average temperature of the lower part of the atmosphere. A second and related factor is the rate at which the temperature decreases with elevation (the “temperature lapse rate”). On some days temperature may be nearly the same from the surface up to mountain peaks. On other days, the temperature decreases rapidly with elevation. For two days with similar average temperatures over the depth of the lower atmosphere, a day with a steep lapse rate (large decrease of temperature with elevation) will have a lower freezing level.

Technical Considerations

Data characteristics

The North American Freezing Level Tracker is a web tool developed to show how freezing level varies with time. Values are based on the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Global Reanalysis. This project produced a self-consistent retroactive record of more than 60 years of global analyses of atmospheric fields in support of the needs of the research and climate monitoring communities. The project involved the recovery and use of original land surface, ship, radiosonde (unit that measures wind speed), pibal (pilot balloon), aircraft, satellite, and other data. These data were then quality controlled and processed with a modern data assimilation system, continually updated with current data in real time (Kistler et al., 2001). A separate North American Regional Analysis with higher spatial resolution also exists, but its record only extends from 1979 onward, not a long enough period for the purposes of the North American Freezing Level Tracker.

A three-dimensional representation of atmospheric structure is now available for the globe on a 2.5 x 2.5 degree grid (about 175 x 125 miles at 45 N latitude). Conditions are analyzed every six hours since 1948, and the data set is updated daily. This has been produced by re-analyzing the original upper air measurements (which have all been saved) using a modern atmospheric model whose properties remain fixed over this entire six-decade interval. From a point high in the atmosphere, well below freezing, a “test point” is moved down to successively lower and warmer altitudes, until the first instance of a freezing temperature is encountered. That distance, in meters above sea level, is then recorded as the freezing level elevation. This is done for each day in the 23,000 days from 1948 until the present. The daily values are averaged into months, and the months can be combined at the convenience of the user. The North American Freezing Level Tracker allows a user to select any point in North America, and smooth the resulting time series in different ways. It should be noted that the concept is most useful in mountainous terrain (such as the western United States), and has little meaning in seasons and locations where the entire atmospheric column is below freezing (for example, northern Canada and Alaska in winter). In summer, the freezing level is nearly always some distance above sea level. This tool, which has other features as well, is available on the Western Regional Climate Center web pages at www.wrcc.dri.edu/cwd/products. At this time a manuscript describing this product is in the early stages of preparation.

Many different kinds of measurement techniques are utilized, including radiosondes launched from sites 200-300 miles apart in the continental U.S. The radiosonde is a small, expendable instrument package that is suspended below a 2 meter (6 feet) wide balloon filled with hydrogen or helium. As the radiosonde is carried aloft, sensors on the radiosonde measure profiles of pressure, temperature, and relative humidity, up to about 100,000 feet. These sensors are linked to a battery powered, 300 milliwatt radio transmitter that sends the sensor measurements to a sensitive ground receiver. The balloon flight may last over two hours until the balloon bursts, at which point the instruments parachute to earth.


Source: National Weather Service

Strengths and Limitations of the Data

The NCEP/NCAR Global Reanalysis is one of the most widely used data sets in climate and atmospheric science. Data have been re-processed in a consistent manner over the entire period. The grid spacing is somewhat large, and the number of atmospheric levels is only modest. Fortunately, freezing level on a daily basis generally exhibits large spatial structure and coherence. Experience in correlating data from Reanalysis to surface temperature records from higher elevations in the Sierra Nevada shows extremely strong correlations on a daily and monthly basis. This area is relatively data rich. One of the radiosonde records used is from Oakland, just upwind from Lake Tahoe, and extending the full history from 1948 to present. Records from numerous aircraft flying, landing and taking off from nearby cities have been routinely incorporated into this data set.

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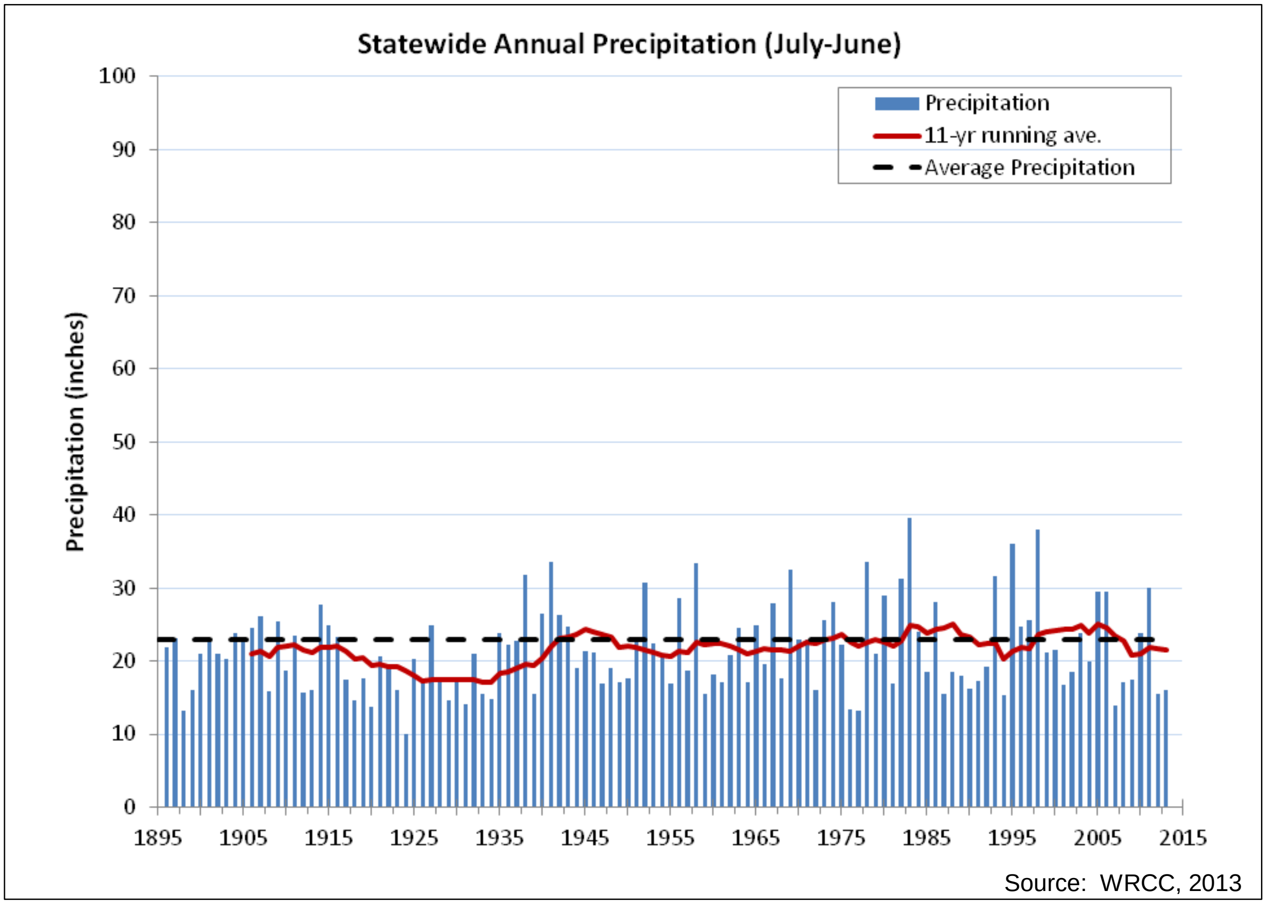
ANNUAL PRECIPITATION (UPDATED)

Large year-to-year variations in annual precipitation are evident, with no apparent trend.



Source: WRCC, 2013

What is this indicator showing?

Annual precipitation in California has been variable from year to year, particularly since the 1930s, with consecutive dry or wet years at many times during the observational record. No clear trend is evident. Annual precipitation ranged from 10.0 inches (in 1924) to 39.6 inches (in 1983); precipitation in 2013 was about 70 percent below average (22 inches, shown as the dashed line in the above graph). Average annual precipitation for selected regions of the state are presented in the table on the right. Individual graphs for each region follow.

Region	Ave. precipitation
Sierra Nevada Region	39.14 inches
North Coast Region	64.42 inches
South Coast Region	17.38 inches
Central Coast Region	25.23 inches

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, an increase in the portion of precipitation falling as rain rather than snow in the mountain areas is expected. Previous research has demonstrated the concern of future limited supply of water (DWR, 2009).

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

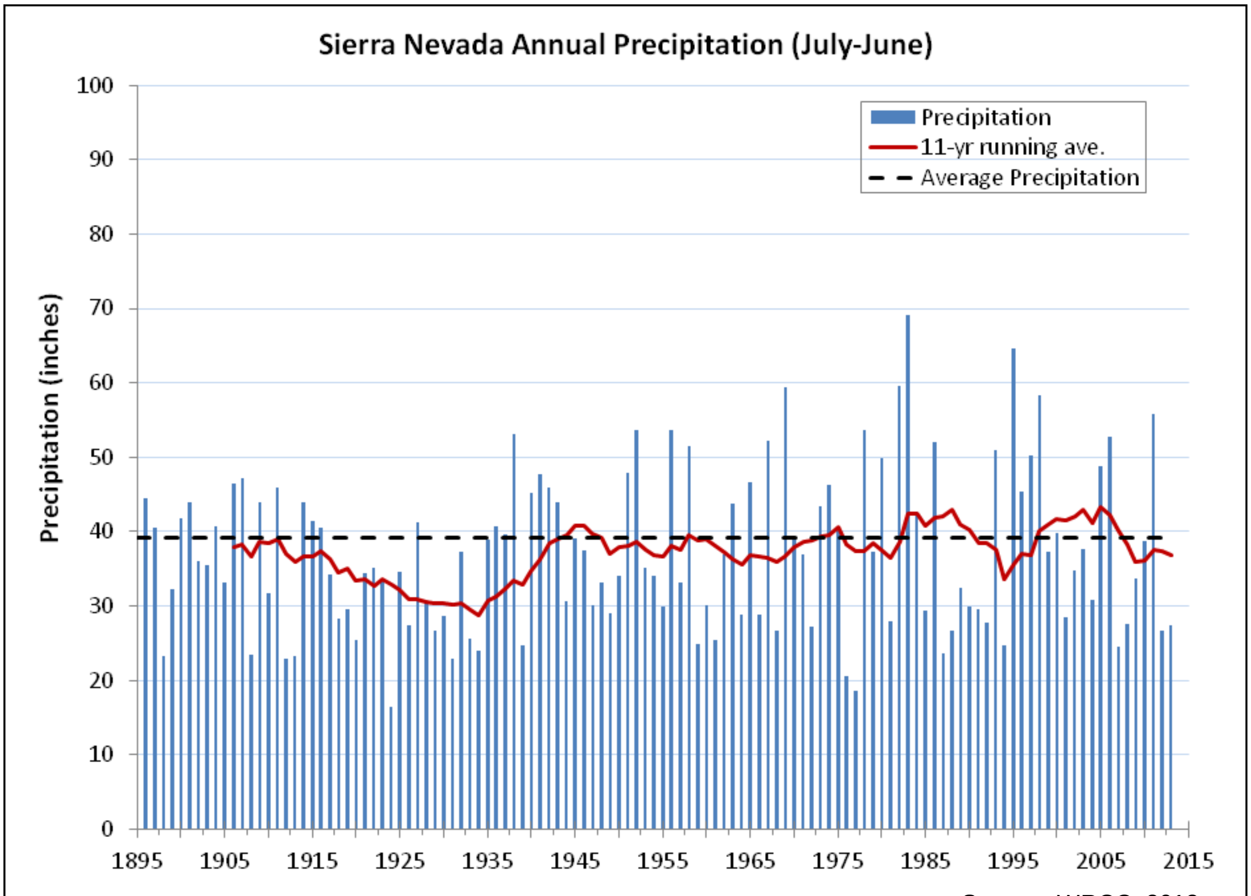
What factors influence this indicator?

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 (November-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, 2013

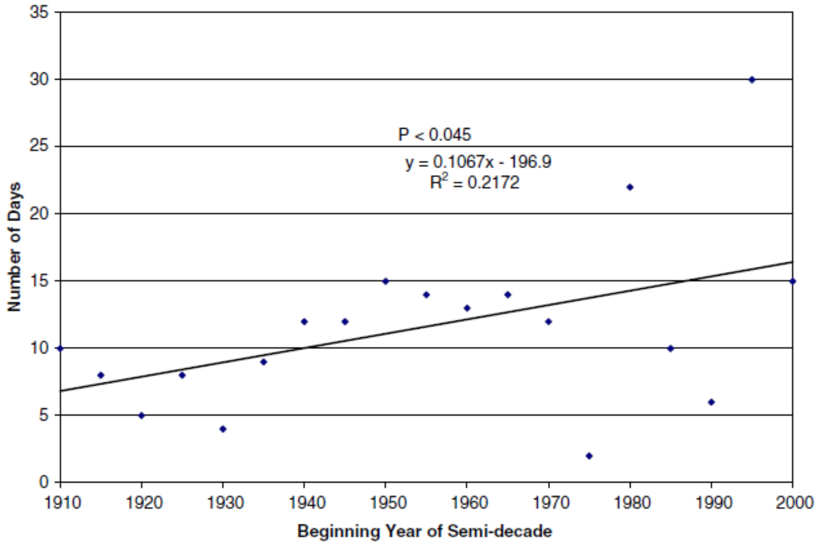
The Sierra Nevada region of California is a key geographic and climatological zone where natural winter snowpack storage provides the warm season water supply. The Sierra Nevada region used here encompasses an area approximately from the Feather River in the north to the Kern River in the south, and 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. Dry years since and including 1976-77 have approached the driest single year ever recorded in 1924. Additionally, the last 35 years have brought some of the wettest and driest winters, including several multi-year wet and dry periods.

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.

Precipitation records at one station in the region, Tahoe City, suggest that wet years are getting wetter and dry years drier (Coats, 2010). The graph below shows an upward trend in the number of days per semi-decade that daily rainfall at Tahoe City exceeded 3.9 centimeters, the 95th percentile value (the top 5 percent) for days with rain. The apparent increase of large positive and negative deviations from the upward trend beginning in 1975 is striking.

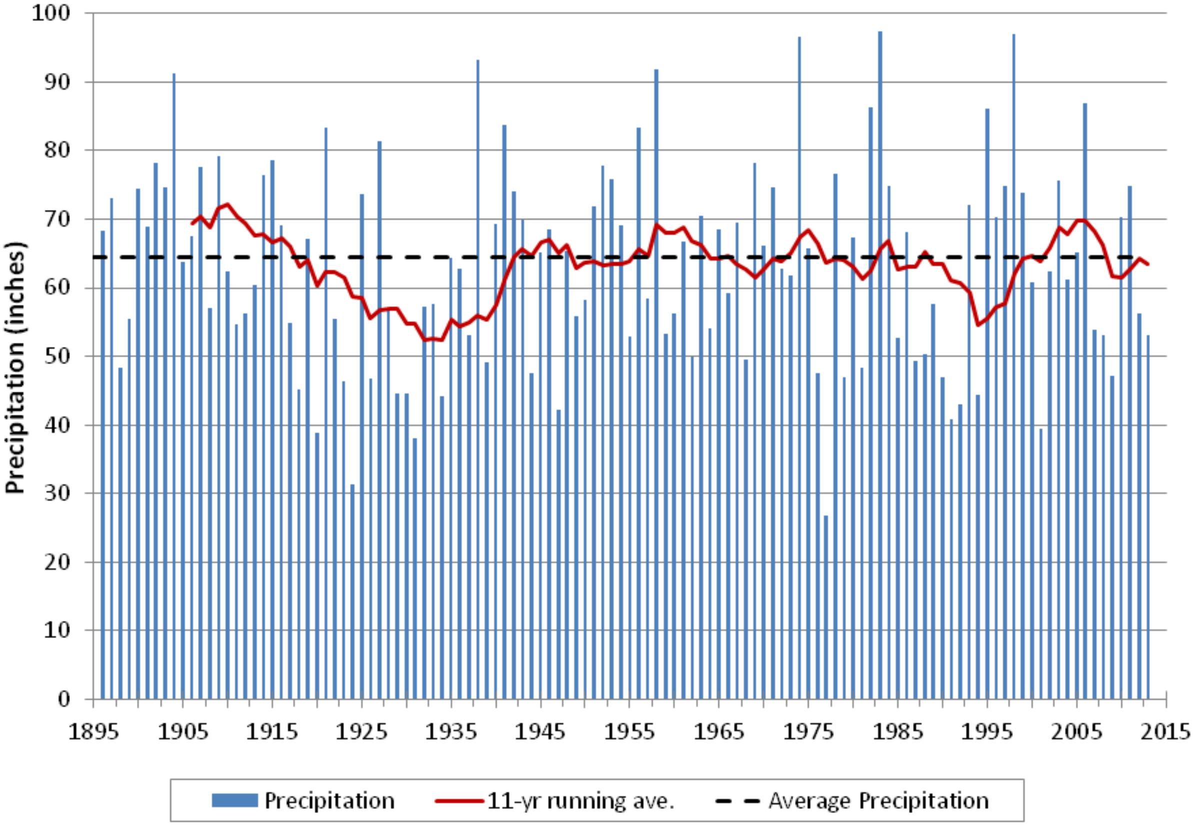
Number of days per semi-decade that daily rainfall at Tahoe City exceeded 3.9 cm, the 95th percentile value for days with rain



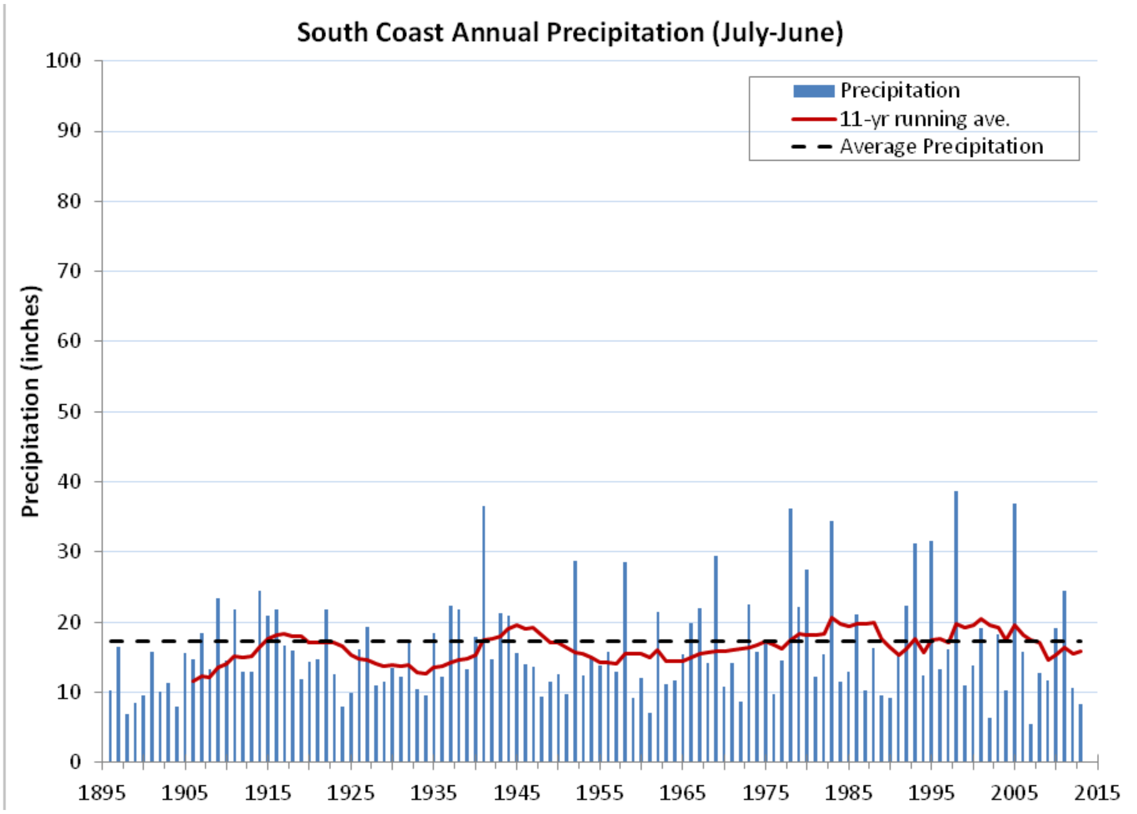
Source: Coats, 2010

Coastal region precipitation trends

North Coast Annual Precipitation (July-June)

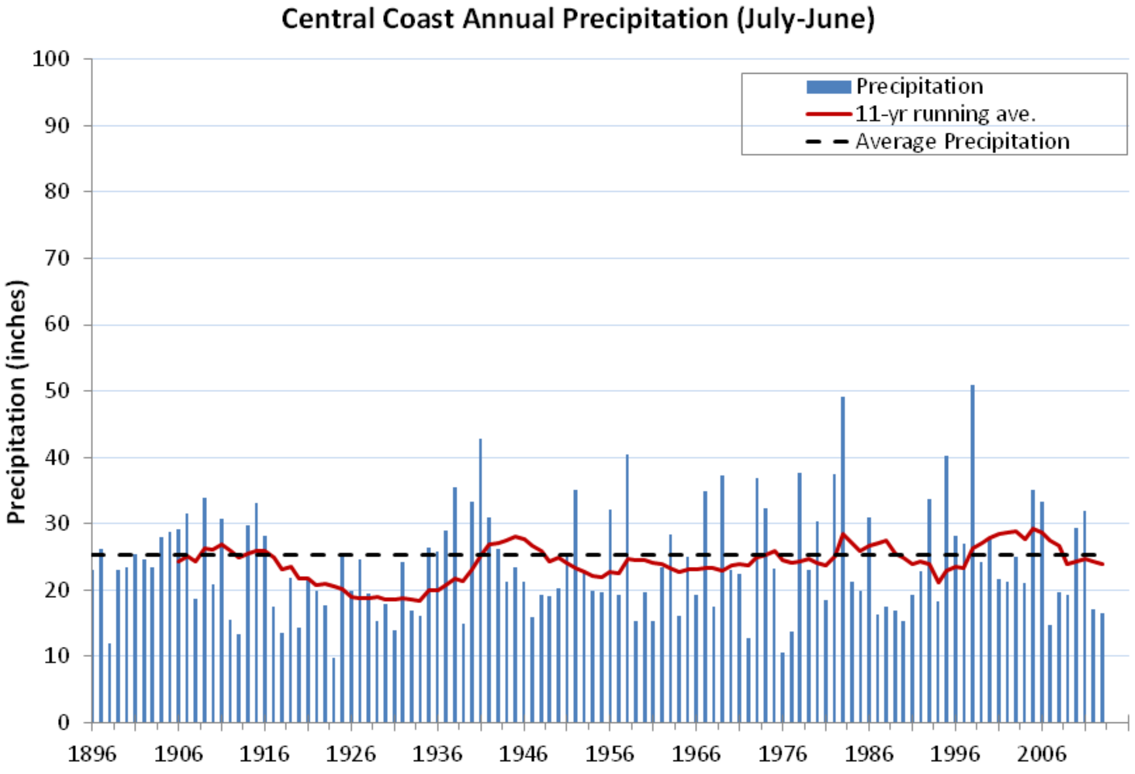


Source: WRCC, 2013



South Coast Annual Precipitation (July-June)

Source: WRCC, 2013



Central Coast Annual Precipitation (July-June)

Source: WRCC, 2013

The large difference in average annual precipitation between the northern and southern California coasts is evident, with the North Coast averaging 34.38” per year, and the South Coast averaging 17.38” 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 1895-2011 is 0 percent over the past century with uncertainty of 12 percent. The North Coast has half as much relative variability (24 percent of the annual mean) as does the South Coast (47 percent). Along the North Coast, 1976-1977 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 +21 percent over the past century with uncertainty of 21 percent, and little evidence of a projected decrease from climate change. For the South Coast, 2006-2007 was the driest winter (5.49”), 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 starting about the middle 1970s.

The Central Coast averages 25.23” per year, with 1924 as the year with the least amount of precipitation at 9.72”, and 1998 the most at 51.02”. The linear trend is +13 percent over the past century with an uncertainty of 17 percent. The region shows an increasing amount of precipitation during the wet years after 1938 similar to, although not quite as pronounced as the increase in the South Coast.

Technical Considerations

Data Characteristics

The data are from California Climate Tracker, an operational database tracker for weather and climate monitoring information. 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 (Abatzoglou et al., 2009).

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 (Daly, Taylor 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 precipitation dating back to 1895.

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., 2009).

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IMPACTS ON PHYSICAL SYSTEMS

Climate is a key factor affecting the characteristics of natural systems. Assessment of global data since 1970 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. (IPCC, 2007f)

INDICATORS: IMPACTS ON PHYSICAL SYSTEMS

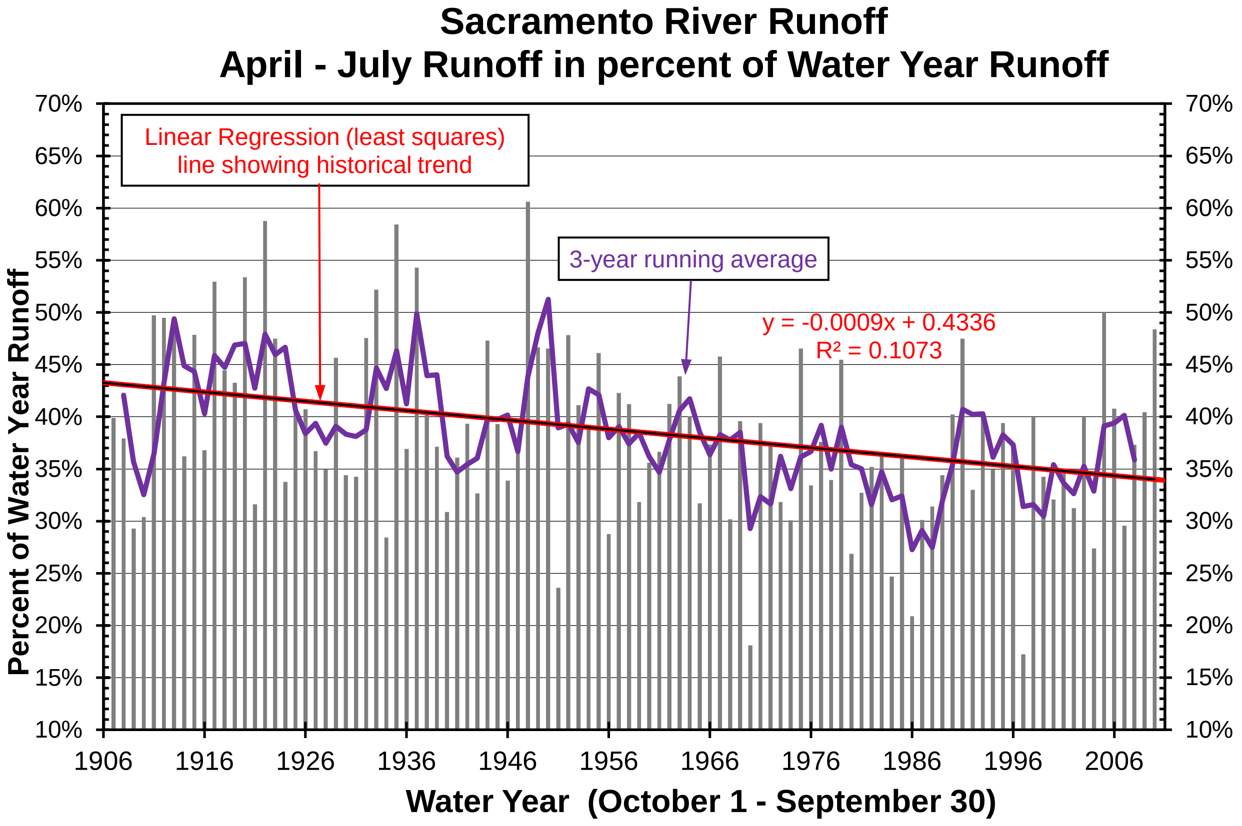
Annual Sierra Nevada snowmelt runoff *(updated)*
Snow-water content *(updated)*
Glacier change *(updated information)*
Sea level rise *(updated)*
Lake Tahoe water temperature *(updated)*
Delta water temperature *(updated)*
Coastal ocean temperature *(updated)*
Oxygen concentrations in the California Current *(no update)*

Reference:

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

ANNUAL SIERRA NEVADA SNOWMELT RUNOFF (UPDATED)

Spring runoff in California has declined over the past century.



Source: DWR, 2011

What is the indicator showing?

Since 1906, the fraction of annual unimpaired runoff into the Sacramento River 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 decreased by about 9 percent. 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. “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; 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.

Why is this indicator important?

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 spring snowmelt runoff may indicate warmer winter temperatures or unusually early warm springtime temperatures.


Source: NPS, 2011

The April through July runoff, primarily from snowmelt, averages around 15 million acre feet (18 billion cubic meters) water which is about 35 percent of the usable annual supply for agriculture and urban needs (Roos and Anderson, 2006). 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, reservoirs and hydroelectric power production. Lower runoff volumes can also impact recreation opportunities, and impair cold water habitat for salmonid fishes (Roos, 2000). Reduced runoff can also impact alpine forests through long summertime drought conditions for young trees (see the *Tree Mortality* indicator, page 132). Less runoff can increase large wildfires through extremely dry vegetation (see the *Large Wildfires* indicator, page 137) and the *Forest Vegetation Patterns* indicator, page 145).

Spring runoff data, along with related snow pack information, are used for water supply and flood forecasting. Spring runoff percentages have declined throughout much of the mountain range:

River Runoff	***% Decline in the 20th Century***
Sacramento River system*	9
San Joaquin River system	6
Kings	6
Kern	8
Mokelumne	7
Trinity	8
Truckee	13
Carson and Walker	5

** includes the Sacramento River and its major tributaries, the Feather, Yuba and American Rivers.*

What factors influence this indicator?

Air temperatures 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 such as winter storms. Other factors, such as the Pacific Decadal Oscillation (PDO) and, possibly air pollution, probably contribute to the patterns observed. The PDO is a pattern of Pacific climate variability that shifts phases on at least an interdecadal time scale, usually 20 to 30 years. It is detected as warm or cool surface waters in the Pacific Ocean which in turn impact coastal and inland climate in Washington, Oregon and Northern California (Mantua and Hare, 2002). There appears to be a PDO effect concurrent with decreasing spring snowmelt percentages due to warming temperatures.

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.

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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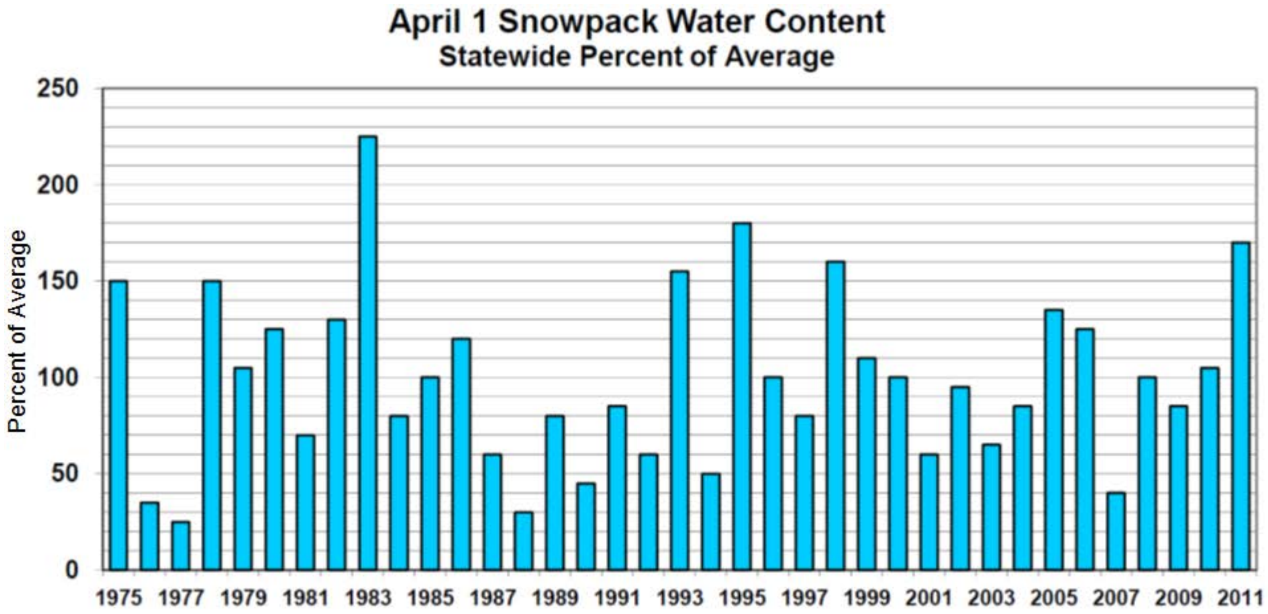
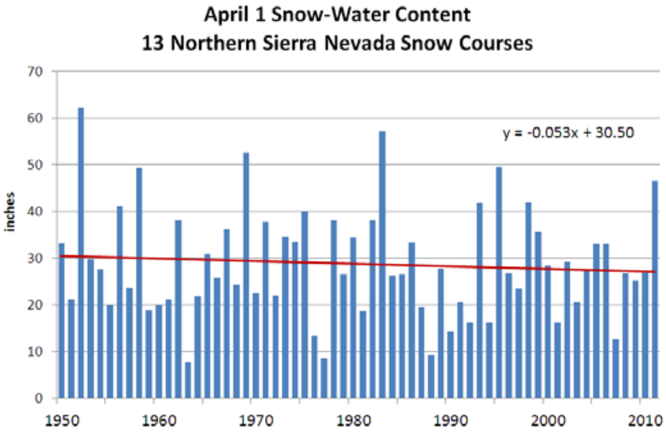
SNOW-WATER CONTENT (UPDATED)

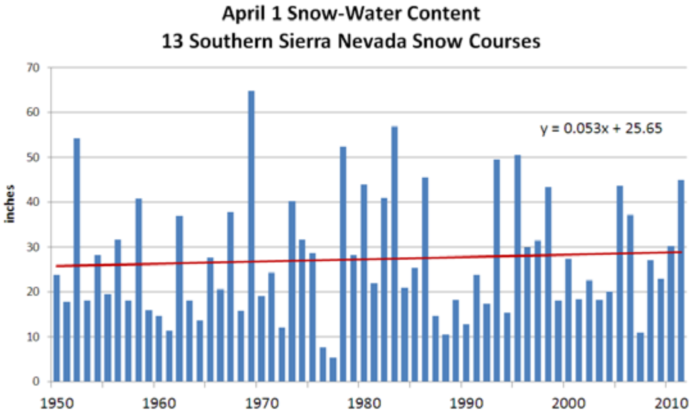
The average total water stored in the state's snowpack on April 1 of each year has stayed roughly the same in recent decades for the state as a whole, but has declined in the northern Sierra Nevada and increased in the southern Sierra Nevada.



Source: DWR, 2011



Source: DWR, 2011



Source: DWR, 2011

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 1975, the April 1 snowpack water content statewide has ranged from about 25 percent of average in the severe drought year of 1977, to around 225 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.

The two lower graphs show the trends in snow-water content in selected Northern Sierra and Southern Sierra long-term snow courses. 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. These graphs of snow-water content show a trend towards less water in the Northern Sierra and a contrasting trend towards more water stored in the snowpack in the Southern Sierra Nevada during the past several decades. April 1 snow-water content has declined by about 10 percent in the northern Sierra Nevada group since 1950, while increasing by about 10 percent in the southern Sierra Nevada group. Together, these suggest little or no net change in the statewide snow-water content averages. However, snowmelt runoff (as shown for the indicator on Annual Sierra Nevada snowmelt runoff) does show a decline, which is presumably related to changes in lower elevation snow levels.

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 snowpack at a given location. Although some of this water will be lost to direct evaporation, most will 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 capacity of the State's major, front-range reservoirs (such as Don Pedro, Oroville, and Friant) is about 20 million acre-feet. Snow has traditionally added about 35 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; likewise, 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 content is determined by winter and spring precipitation totals and air temperatures. Elevation matters: One would expect less change in the higher elevation snow zones and more in the lower snowpack zones. To a lesser extent, snow-water content may be influenced by the amount of solar radiation that falls on the snowpack in each season, which, in turn, depends on cloudiness and timing of the beginning of the snowmelt season (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 content could increase in those areas that are still cold enough to receive snowfall (above the retreating snowlines); if precipitation decreases, snow-water content 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).

A potentially confounding factor in the variation and trends in April 1 snowpack is the effect of dust and other contaminants on both the initial formation of mountain snowpacks and on snowmelt timing. Recent field campaigns of measurements and modeling have provided potentially important indications that the presence or absence of dust in the atmosphere, including dust carried to California by high-altitude winds from Asia, may help to determine amounts of snowfall over the Sierra Nevada, which in turn could contribute to variations and trends in April 1 snowpack (Ault et al., 2011). Other recent studies have helped to quantify important influences on snowmelt timing and, ultimately, amounts that are due to springtime snow albedo (reflectivity) changes associated with dust (mostly from within the region) falling onto snow surfaces across the Western US (e.g., Painter et al., 2010). Both of these factors likely play roles in past and future variations of April 1 snowpack amounts, but the long-term past and future trends in these additional factors in California remain largely unknown at present.

The declines in snow-water content 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 snowpack 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 (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 snowmelt.

Additionally, the conflicting trends may be due to differences in elevation between the northern and southern snow courses. The average elevation of the northern Sierra group of 13 courses is 6,900 feet, whereas the average is 8,900 feet for the southern group.

Technical Considerations

<u>Data Characteristics</u>

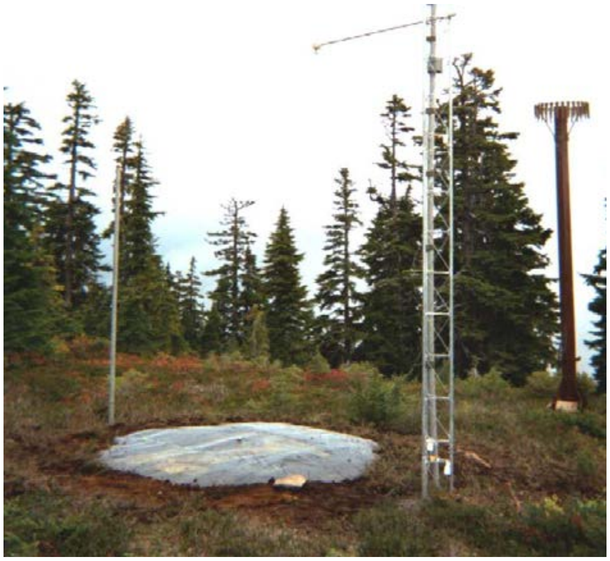
As indicated previously, snow-water content has traditionally been measured by weighing cores of snow pulled from the whole depth of the snowpack at a given location. Since the 1930s, within a few days of the beginning of each winter and spring month, snow course measurements have been performed by skiing 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 are measured, the weights are converted to a depth of liquid water that would be released by melting that weight of snow; the results from all the measurements at the snow course are averaged to arrive at estimates of the snow-water content at that site.

There is a need to obtain daily information on the accumulation and melting cycles in the snowpack. Water project operators and users like to know what the effect on the pack is from individual storms or hot spells. For this reason an automatic snow sensor network (often called snow pillows) has been developed and deployed over the last 30 years to monitor the daily status of the snowpack. There are now approximately 130 snow sensor sites from the Trinity Alps to the Kern River, with 36 sites included from the Trinity area south to the Feather and Truckee basins, 57 sites from the Yuba and Tahoe basins to the Merced and Walker basins, and 36 sites from the San Joaquin and Mono basins south to the Kern basin. A list of the snow sensor sites used and the most recent summary statistics are available at http://cdec.water.ca.gov/cgi-progs/snow/DLYSWEQ.

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 (see photograph below). Snow pillows are large (10 foot (') diameter), flat, flexible tanks or a group of four interconnected 4' x 5' sheet metal 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. This 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.



Source: NRCS, 2011

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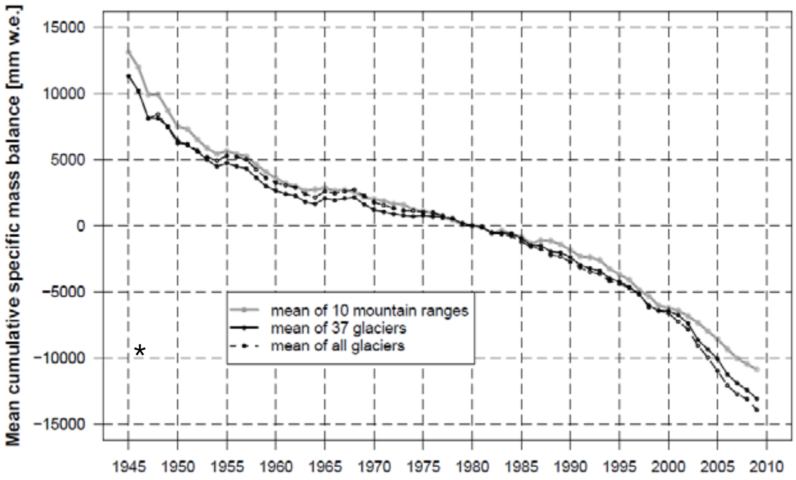
GLACIER CHANGE (UPDATED INFORMATION)

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

> *The 2009 climate change indicators report presented an indicator showing decreases in the surface area of seven glaciers in the Sierra Nevada. Additional photographs for two glaciers are presented here, along with new information on glacier mass changes globally.*

Global glacier mass has been decreasing since 1945, as shown in the graph on the right. A strong mass loss occurred in the first decade after the start of measurements in 1946, slowing down in the second decade (1956–1965). A moderate ice loss occurred between 1966 and 1985, followed by a subsequent acceleration until 2009. The graph is based on standardized observations on glaciers around the globe collected by the World Glacier Monitoring Service (WGMS, 2011).

Global average glacier mass changes



Source: WGMS, 2011

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*The mass of each glacier at a given year relative to its mass in 1945/46 is calculated; an average of these values across glaciers is then derived for each year; mm we. – millimeters of water equivalent

Goddard Glacier, late summer 1908

G. K. Gilbert

2004

H. Basagic

Dana Glacier, late summer 1883

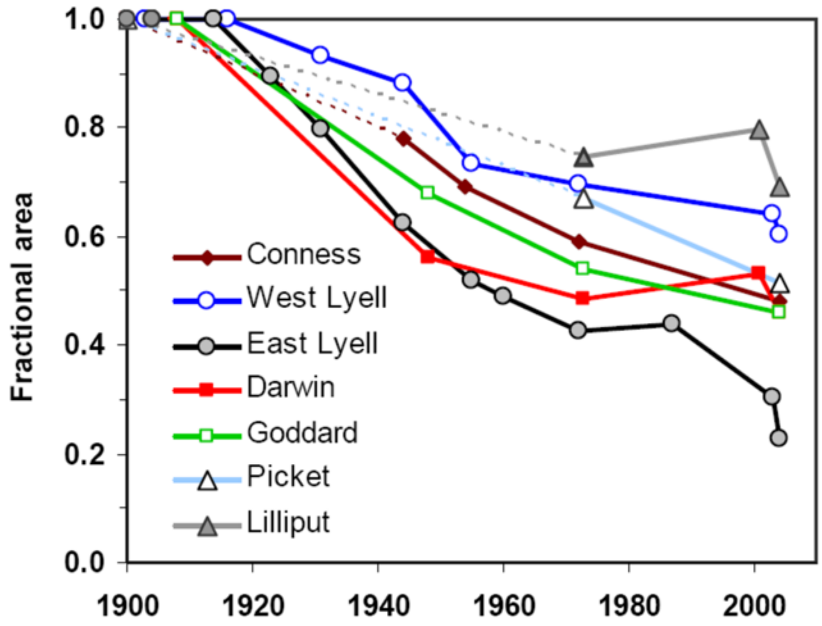
I.C. Russell

2004

H. Basagic

The discussion of the glacier change indicator from the 2009 report is reproduced below.

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 and West lobes

1903

G. K. Gilbert

2004

H. Basagic

Darwin Glacier

1908

G. K. Gilbert

2004

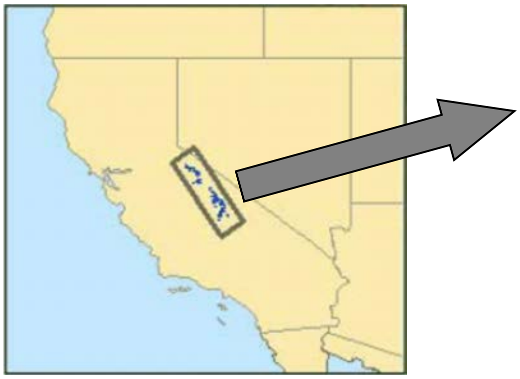
H. Basagic

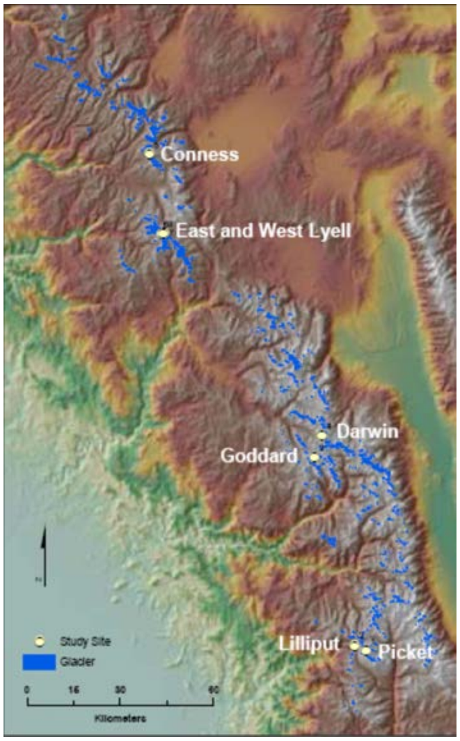
What is the indicator showing?

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 late summertime 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: H. G. 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 (IPCC, 2007g).

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 number of intervals 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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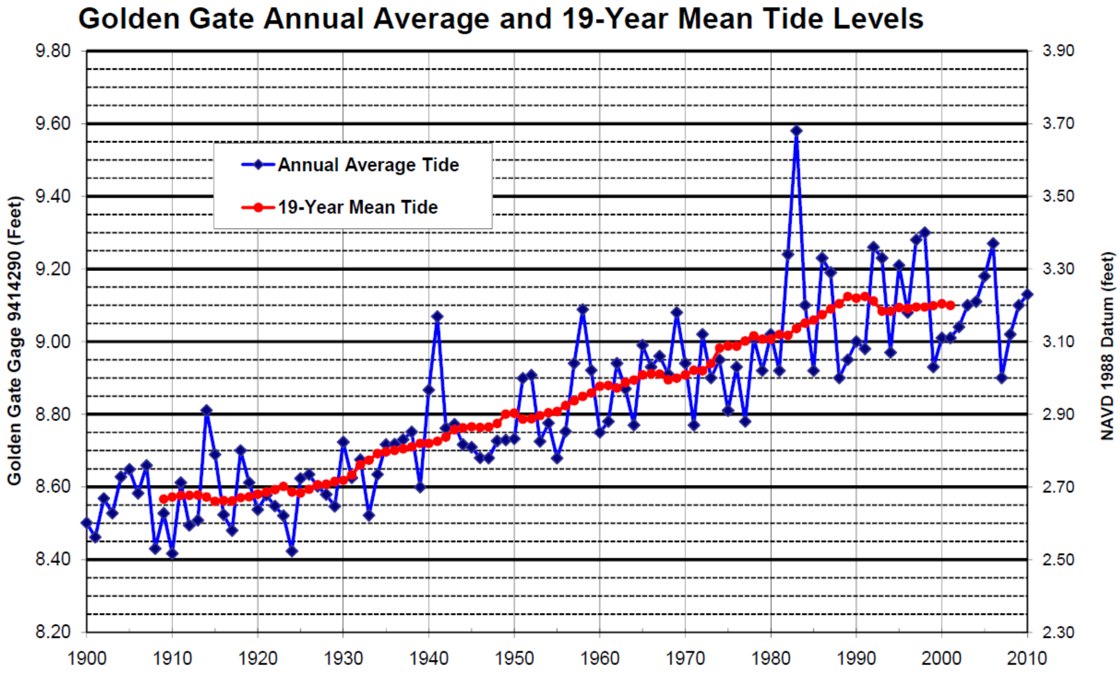
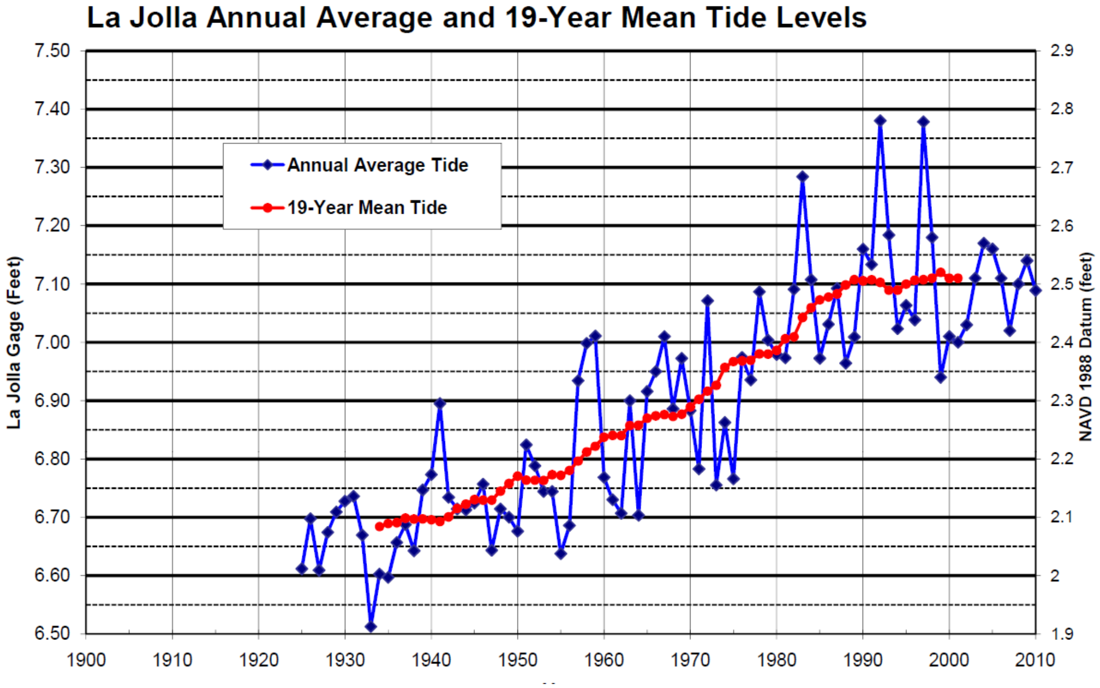
SEA LEVEL RISE (UPDATED)

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: DWR, 2011

What is the indicator showing?

The indicator shows the rising trend in sea level (measured as annual average tide 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. (Flick, Murray et al., 1999). The graphs show that the increase appears to have leveled off during the past 20 years. The latter is in contrast to the increasing rate of rise measured by worldwide satellite altimetry. Two possible explanations for the difference are discussed below (see *What factors influence this indicator?)*

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, 2007h), 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 et al., 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, 2007h). 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 portions of the San Francisco Bay Delta system, erosion of cliffs and beaches, saltwater contamination of some groundwater aquifers and drinking water, and impacts on roads, causeways, storm drains, sewage treatment plants 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. Coastal flooding hazard maps and data for informational purposes have been prepared by the Pacific Institute with support from the California Department of Transportation, the Ocean Protection Council, and the United States Geological Survey (Bay Area Inundation). The maps may be accessed at: www.cal-adapt.org.

What factors influence this indicator?

Along California's coast, sea level already has risen by an average of 7 inches over the last century (three inches at Los Angeles, eight inches at San Francisco, and an estimated six inches at La Jolla near San Diego). 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 sea level 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. 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.

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.

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, 2007h). 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.

The measurements at San Francisco Bay and La Jolla show a leveling off of sea level rise in the past two decades. This is in contrast to the trends observed globally showing continued rise at the rate of 3 mm/year (0.12 inches/year). The reasons for the discrepancy are not clear. One possibility is that a change in wind patterns following a shift in the mid-1970s from cold to warm phases of the Pacific Decadal Oscillation—a roughly decade-long pattern of Pacific climate variability—may have mitigated the rising trend in regional sea level rise on the west coast; an eventual phase shift may result in a resumption of sea level rise at a rate approaching or exceeding the global rate (Bromirski et al., 2011). Another possibility is that the ocean may not respond like one big bathtub; subtle shifts in the location of mass as polar ice melts and its water is redistributed might cause different responses in different regions of the globe instead of a uniform rise. Wind pattern changes can also be a part of the distribution. These questions illustrate the importance of continued measurements of sea level at long running tide gage stations. (Roos, personal communication, 2011).

In view of the huge variation in projections of future sea level later this century, the California Department of Water Resources, along with other State agency partners, asked the National Research Council (NRC) to address planning for future sea level rise, including estimation of a range of likely amounts of sea level rise in 2030, 2050, and 2100. Three federal agencies and the States of Oregon and Washington have joined the study. The committee convened by the NRC recently released a report presenting regional projections for California, Oregon, and Washington that show a sharp distinction at Cape Mendocino in northern California. South of that point, sea level rise is expected to be very close to global projections (relative to 2000, projections are 4 to 30 centimeters (cm) (1.6 to 11.8 inches (in) by 2030, 12 to 61 cm (4.7 to 24 in) by

2050, and 42 to 167 cm (16.5 to 65.7 in) by 2100). However, projections are lower north of Cape Mendocino (-4 to +23 cm by 2030 (-1.6 to 9.1 in), -3 to +48 cm (-1.2 to 18.9 in) by 2050, and 10 to 143 cm (3.9 to 56.3 in) by 2100, relative to 2000), where land is rising largely due to plate tectonics (NRC, 2012).

Technical Considerations

Data Characteristics

The San Francisco data are obtained from the Golden Gate tide gage (see photograph), 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. 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 two decades. This agrees with a much broader collection of tide data that show that global average sea level rose between 4 to 12 inches during the 20th century. The tide gage at La Jolla shows an increase in mean sea level of approximately 4.8 inches (0.4 foot) in the past 80 years, or looking back, perhaps 6 inches (0.5 foot) per century. The Golden Gate rate would be comparable at about 7.2 inches (0.6 foot) 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.

Source: NOAA, 2011

Monthly or yearly mean sea level statistics are derived by averaging near-continuous water level measurements from tide gages. Sea level fluctuates at all timescales, but tide gages 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 with warmer water, and lower in La Niña years like 1999 and 2008 with cooler water.

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 gages 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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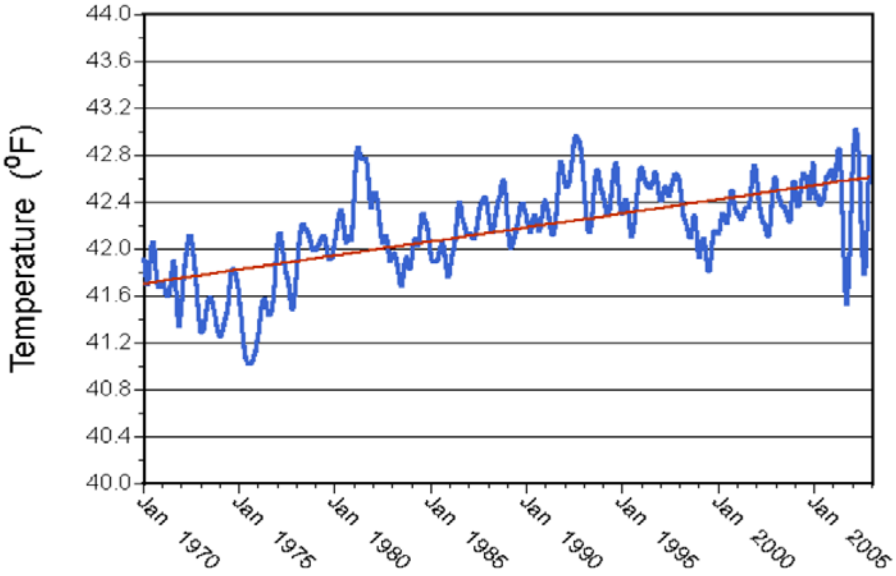
LAKE WATER TEMPERATURE (UPDATED)

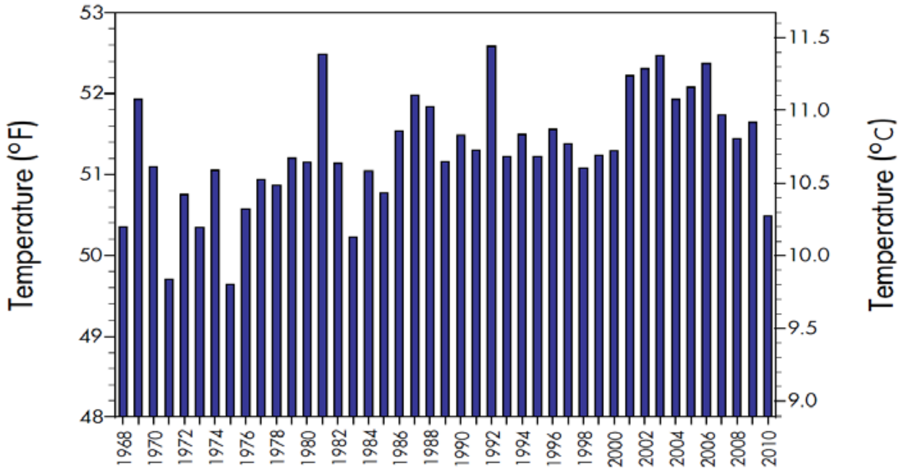
Lake Tahoe and other California (and Nevada) lake waters are warming.

Average water temperature, Lake Tahoe



Source: UC Davis, 2011

Surface water temperature, Lake Tahoe



Source: UC Davis, 2011

What is the indicator showing?

The two different metrics presented in the first two graphs show that Lake Tahoe waters are warming. Volume-averaged lake temperatures have increased by nearly a full degree Fahrenheit (°F) since 1970 (top graph). Likewise, surface water temperatures show an increasing trend—although the average temperature for 2010 was relatively cool at 50.5°F, down from 51.6°F in 2009, and only slightly higher than the average of 50.3°F for 1968 (bottom graph).

In addition, warming has been observed at six lakes in California and Nevada (including Lake Tahoe) based on temperature data derived from satellite observations (see graphs, next page). All the lakes show a significant warming trend since 1992 for summer (July through September) nighttime temperatures, ranging from increases of 0.05 degree Centigrade (^{o}C) per year at Clear Lake to 0.15^{o}C per year at Lake Almanor and Mono Lake. The lakes exhibit a fairly similar rate of change, with the mean warming rate being 0.11 $\pm$ 0.03^{o}C per year.

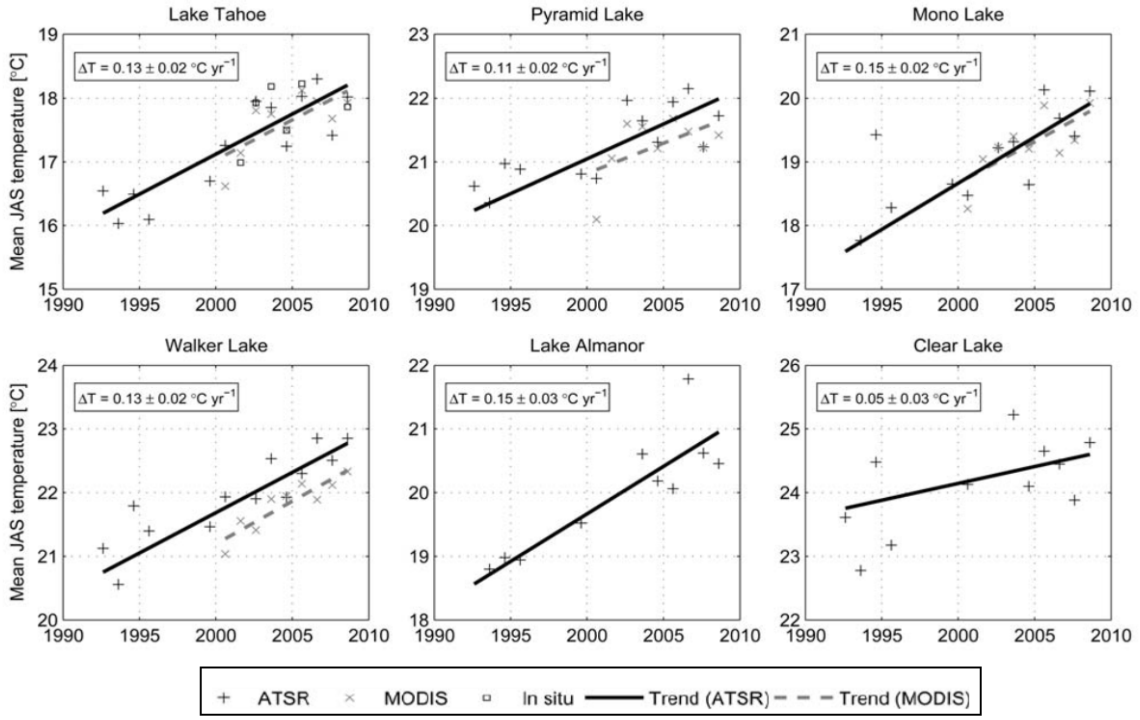
Why is this indicator important?
The chemical, physical and biological characteristics of lakes can change as a result of warming temperatures. A global assessment of climate change impacts on inland aquatic ecosystems confirmed earlier conclusions that rising temperature will lower water quality in lakes by, among other things, increasing thermal stability and altering mixing patterns (IPCC, 2007i). These, in turn, result in changes in productivity, species composition and organism abundance, as well as phenological shifts. Warmer waters in Lake Tahoe may already be making favorable conditions for certain algae and some introduced species such as large-mouth bass and bluegill. In the last few years, microalgae have proliferated in the surface waters of the lake. Their size is such that they are having a significant impact on water clarity.

California Tahoe Conservancy, 2009

Lake Tahoe is a 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 (CTC, 2008).

Lake Tahoe is 35 kilometers (21.8 miles) long and has a surface area of 500 square kilometers (193 square miles) and a total volume of 157 cubic kilometers (127 million acre feet). Its maximum depth of 501 meters (1,644 feet) 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.

Trends in summer (July through September) nighttime surface temperatures
4 California and 2 Nevada lakes

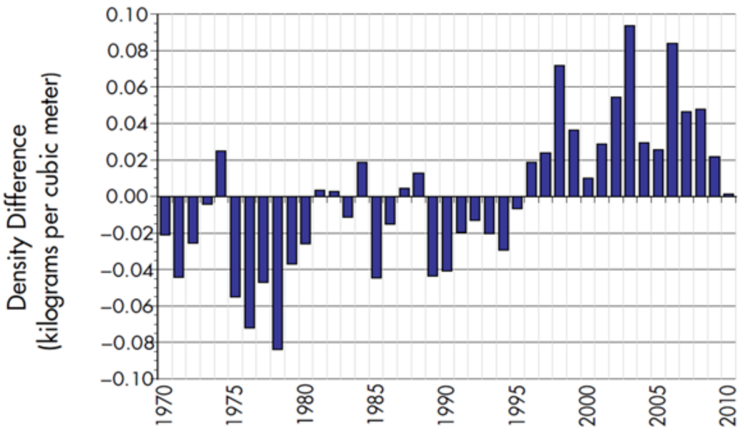


Source: Schneider et al., 2009

Overview of the study sites with detailed maps of lakes on left and right. Color-coded July through September (JAS) air temperature trends (1992-2008) are shown in the inset box.

Physical data from Lake Tahoe illustrate some of these impacts. The graph on the right shows that density stratification has generally increased since 1970. Warmer shallow waters become lighter, or less dense. Density stratification is measured using “density difference” (Y axis), calculated as follows: the difference in densities between the lake’s deep waters (100 to 165 feet) and shallow waters (0 to 33 feet) is determined, then subtracted from the average density of the lake. Density difference was relatively low for the year 2010, following more than a decade of higher than average values. Increased stratification reduces water movement across the thermocline (the transition zone between the upper layer and the cooler waters of the deeper layer). This reduces the mixing that brings nutrients from the deep waters to surface waters (Bates, 2008).

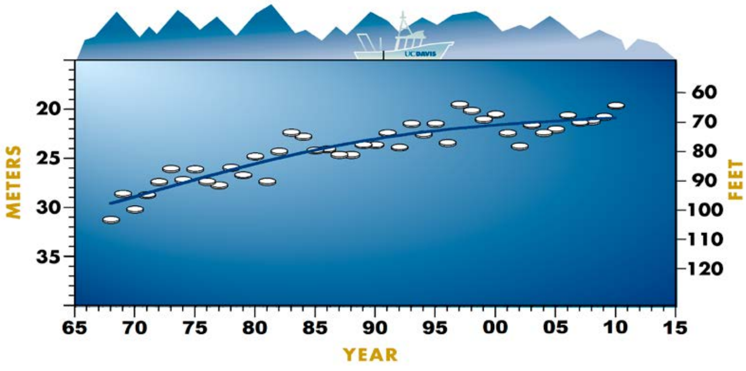
Density stratification at Lake Tahoe



Source: UC Davis, 2011

Reduced mixing may prolong the periods of reduced lake clarity 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. Fine particles scatter light and limit transparency. Decreased mixing helps retain small particles in the epilimnion (upper layer of the lake), where they have maximum impact on lake clarity. The decreasing transparency in the lake may, in turn, decrease the depth of the layer in which solar radiation input is concentrated, further increasing thermal stratification.

Annual average Secchi depth at Lake Tahoe



Source: UC Davis, 2011

The graph on the left shows the depth below surface at which a disk (called a Secchi disk) can be seen when lowered into the lake; the clearer the waters, the greater the depth at which the disk is visible. Each value plotted is the average of 20 to 25 readings made throughout the year. In 2010, an average depth was 64.4 feet, the second shallowest depth ever recorded (the shallowest was 64.1 feet in 1997).

Although lake clarity since 1968 has been declining overall, the rate of decline has slowed somewhat over the last decade, with notable differences between winter and summer clarity. Winter clarity has been showing a general improvement, while summer clarity continues to decline over the same period. Increased thermal stability in the water column appears to be producing conditions that favor small diatoms and other algae close to the surface, scattering light and decreasing transparency. Long-term monitoring data are essential for better understanding the seasonal differences and the factors affecting lake clarity (UC Davis, 2011).

Lake temperature data for the lakes described here add to the body of knowledge about warming trends in lakes throughout the world. Because they are sensitive to climate, respond rapidly to change, and integrate information about changes in the land areas that drain into them (catchment), lakes serve as good sentinels for climate change. Certain changes in the physical, chemical and biological properties of lakes represent responses that are either directly influenced by climate, or are indirect changes resulting from climate influences on the land areas that drain into the lake (catchment) (Adrian et al., 2009). Given that freshwater is one of the resources most jeopardized by a changing climate, tracking changes that are detrimental to lake water quantity or quality is critically important (Williamson et al., 2009).

What factors influence this indicator?

A number of studies have shown that lake temperatures reflect warming trends in air temperature (Adrian et al., 2009). An analysis of the spatial patterns in lake temperature trends compared to air temperature trends for the summertime months (July through September) showed good agreement globally, although there are areas in which lake waters appear to warm more rapidly than the surrounding air temperature, such as the Great Lakes and lakes in Northern Europe (Schneider and Hook, 2010).

Surface water temperatures at the six lakes presented here also appear to be warming more rapidly than the mean surface air temperature. Other investigators reported the same observation at Lake Superior (Austin and Colman, 2007). They suggested that the effect is caused by declining winter ice cover, resulting in a longer period over which the lake warms during the summer. The mean summertime air temperature trends for the study region ranged from 0.01 to 0.06^{o}C/year, compared to the nighttime warming rates for the lakes (0.05 to 0.15^{o}C/year) (Schneider, Hook et al., 2009). The use of the average of all nighttime summertime temperatures for the three-month period from July through September for each year in order to assess lake temperature trends allows the annual temperature peak (around August) to be captured, while also providing a reasonably large sample size and eliminating diurnal heating. For Lake Tahoe specifically, analysis of data from the Tahoe City meteorological station showed significant increases in average summertime minimum air temperatures—0.03^{o}C/year since 1910, and a more rapid increase of 0.06^{o}C/year between 1992 and 2008; nighttime lake water surface temperatures, by comparison, warmed by 0.13^{o}C/year (Mastrandrea et al., 2009; Schneider et al., 2009).

An analysis of historic trends in the Tahoe basin's hydroclimatology shows, among other things, strong upward trends in air temperature (especially minimum daily temperature), a shift from snow to rain and a shift in snowmelt timing to earlier dates (Coats et al., 2006; Coats, 2010). These data are presented in the appendix to this indicator.

Technical Considerations

Data Characteristics

A four decade-long data set collected on the Lake Tahoe ecosystem by the University of California, Davis and its research collaborators provides the basis for a number of measurements used for monitoring progress toward restoration goals for Tahoe and desired conditions. 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 meters from the surface to a depth of about 100 meters have been taken approximately weekly since 1969, and at 1-meter increments to a depth of 125 meters 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 meters have been taken at least monthly since late 1969 (Coats et al., 2006).

The six lakes in the study by Schneider, et al. were selected based on the possibility of extracting a clear temperature signal over the lake; hence, the surface area and shape of the lakes were the primary selection criteria. Lake temperatures were obtained using satellite thermal infrared imagery from two sources: the Along Track Scanning Radiometer (ATSR) series (data from three different satellites) and the Moderate Resolution Imaging Spectrometer (MODIS) imagery. Over 5,000 ATSR scenes covering the six lakes from 1991 through 2008 were available, providing an 18-year record of water surface temperature. The MODIS data were used to supplement and corroborate the results from the ATSR data. No MODIS data were available for Lake Almanor and Clear Lake. The thermal images were processed, and lake surface temperatures computed from the brightness temperatures, as described in Schneider et al., 2009. Nighttime temperature recordings were used because they provide better accuracy than daytime data due to the absence of differential solar heating. *In situ* surface temperature measurements from Lake Tahoe's Automated Validation Site were used to validate the satellite imagery results. This site provides highly accurate observations of both surface and bulk water temperature at intervals of two minutes.

Strengths and Limitations of the Data

Temperature data for Lake Tahoe have been collected as part of an ongoing long-term monitoring program to monitor changes in the lake. Weekly to monthly temperature profiles have been collected since 1969; surface measurements began in 1964. A variety of thermometers and digital thermographs have been used at the Index Station over the years. Although the sensitivity, accuracy and calibrations of these instruments have varied over time, these data are adequate for characterizing the thermal structure of the epilimnion and thermocline. Temperatures at the Midlake Station were originally measured at 13 depths with mercury reversing thermometers, as follows: a protected thermometer, unaffected by pressure, records the temperature at reversal depth; readings from this thermometer are corrected for glass expansion and, along with a second, unprotected thermometer affected by pressure in deep water, provide measure of the actual depth of the temperature reading (Coats et al., 2006). These instruments were accurate to 0.01^{o}C. More recently temperature is measured using a high precision thermistor that is part of a suite of instruments on a Seabird SBE-25 profiler. Accuracy of the thermistor is 0.001^{o}C. The Seabird measures at a rate of 8 times per second as it falls through the water at a velocity of 60 cm/sec.

Lake temperature data derived from thermal infrared satellite imagery (ATSR and MODIS), when validated against corresponding *in situ* data for Lake Tahoe, were found to agree very well over the entire range of temperatures. This, along with an additional assessment of inter-sensor bias between all ATSR sensors, indicates that accurate and stable time series of lake surface temperature can be retrieved from ATSR and MODIS data.

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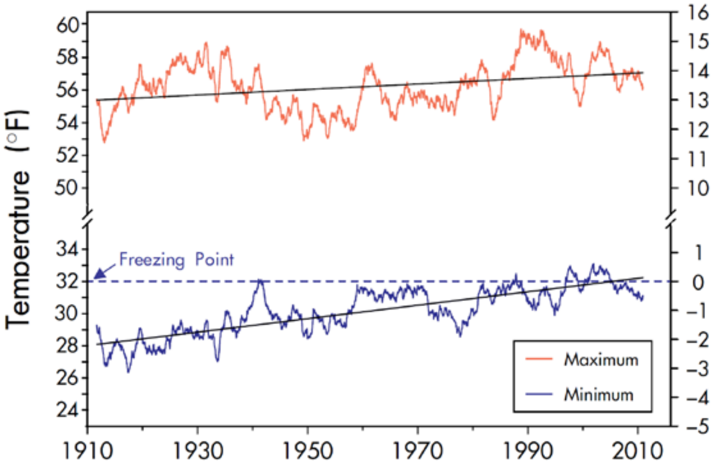
APPENDIX: Lake Tahoe Meteorological Data

The increasing temperature of Lake Tahoe is accompanied by meteorological trends that show warming.

Daily air temperatures, Lake Tahoe

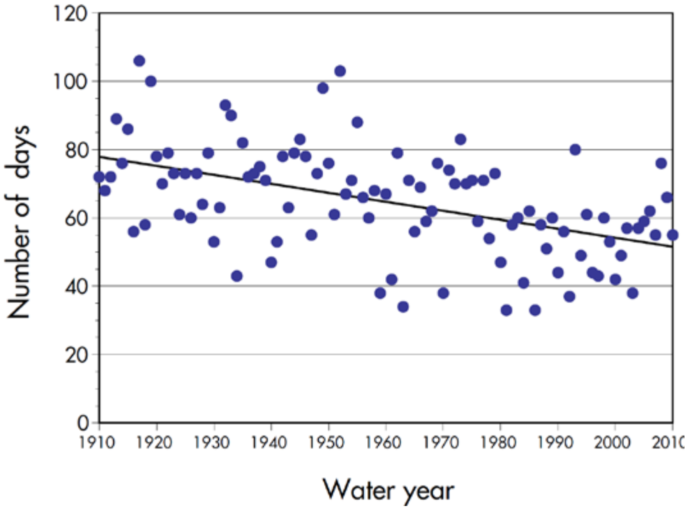


Source: UC Davis, 2011

At Tahoe City, daily minimum temperatures have increased by more than 4°F, while daily maximum temperatures have increased by less than 2°F over the past century. Minimum temperatures above the freezing point of water indicates more rain, less snow and earlier snowmelt. Other related parameters reflect similar warming patterns, such as those presented in the graphs that follow.

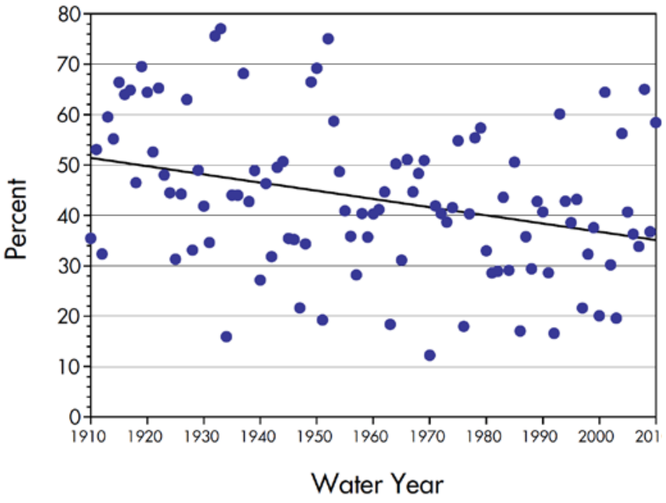
Over the past century, the number of days when air temperatures averaged below freezing (32°F) has declined by about 30 days. In addition, the fraction of total precipitation falling as snow has declined, from about 52 percent in 1910 compared to about 34 percent in present times. These data assume that precipitation falls as snow whenever the average daily air temperature is below freezing.

Below-freezing air temperatures



Source: UC Davis, 2011

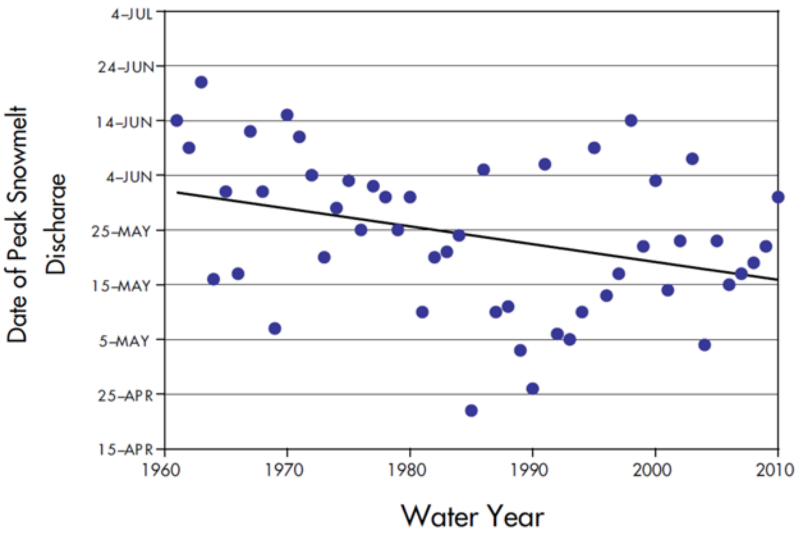
Snow as a fraction of annual precipitation



Source: UC Davis, 2011

Daily river flows increase throughout spring as the snow melts because of rising air temperatures, increasing solar radiation and longer days. Peak snowmelt is defined as the date when daily river flows are the highest for the year. This date has shown a declining trend overall since 1961, and has shifted earlier by about 2.5 weeks. The data shown are based on the average snowmelt from the Upper Truckee River, Trout Creek, Blackwood Creek, Ward Creek and Third Creek.

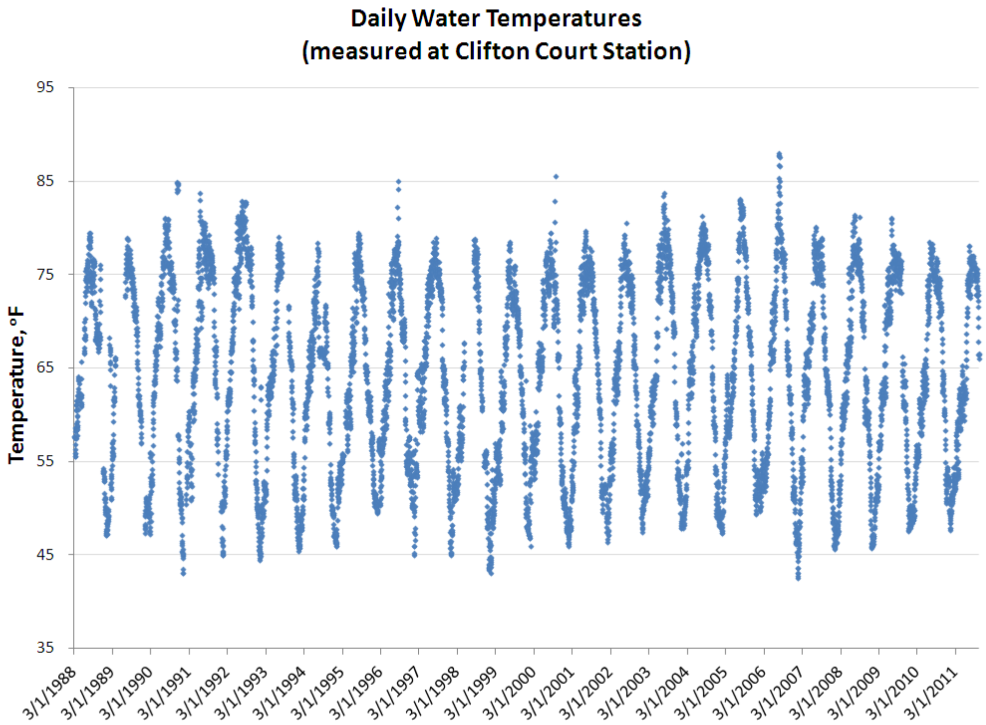
Shift in snowmelt timing



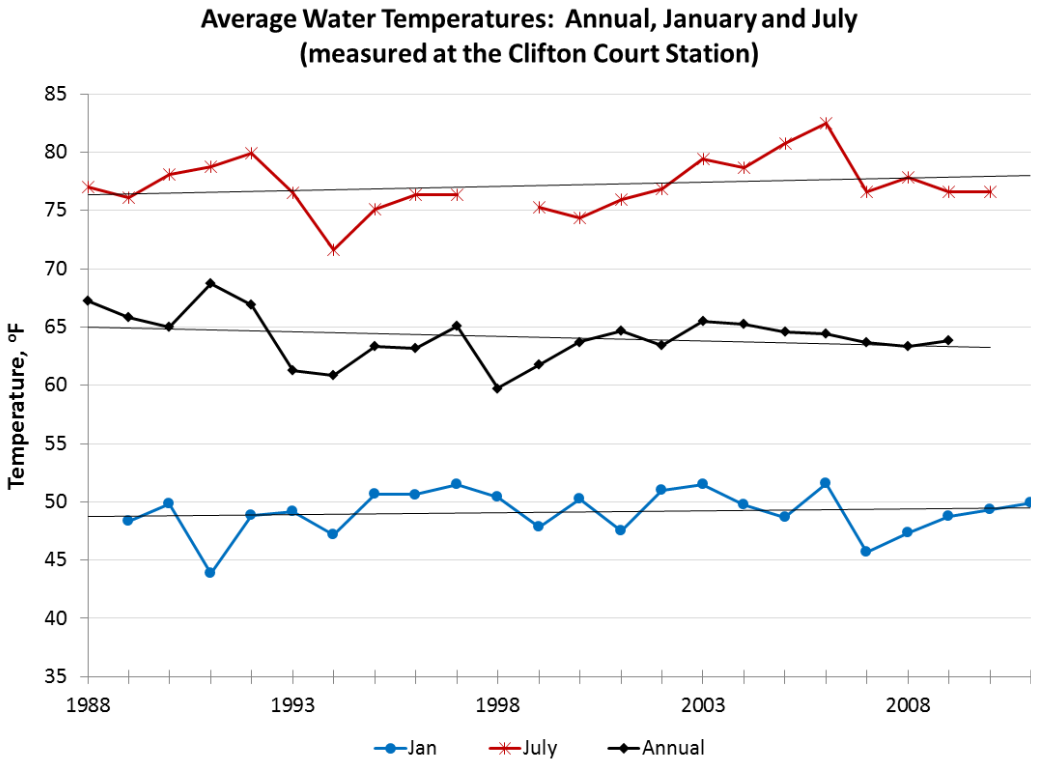
Source: UC Davis, 2011

DELTA WATER TEMPERATURE (UPDATED)

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



Source: DWR, 2011



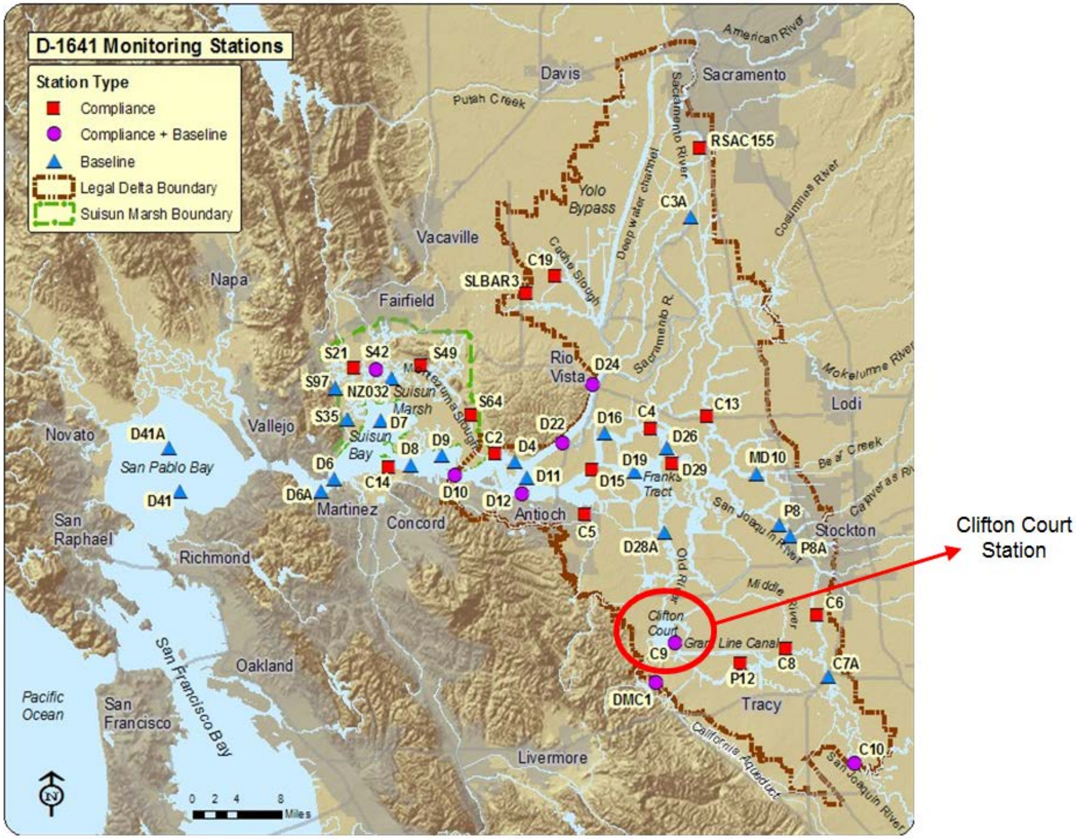
Source: DWR, 2011

What is the indicator showing?

No single location can serve as being representative of water temperatures all over the state. 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 on the preceding page 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: DWR, 2012

Clifton Court water temperatures exhibit a great deal of seasonal variability. However, less year to year variability has been observed in recent years. Annual temperatures have ranged over almost 10ºF since 1988, with a minimum of 59.7^{o}F in 1998 and a maximum of 68.7^{o}F in 1991 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 in that they include 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.

A recent evaluation of the potential for water temperature increases in the Delta due to projected climate changes to impact Delta ecosystems showed that both long-term averages of Delta water temperatures and the frequency of extremely warm spells in Delta water temperature are likely to increase as California's climate changes and warms (Cloern et al., 2011). In that study, under optimistic and pessimistic versions of future California climate changes, Delta water temperatures were projected to rise by about 0.22^{o}F and 0.54^{o}F per decade in the 21st Century and, perhaps notably, these temperature increases were projected to be somewhat greater than those in the Sacramento River proper. At the same time, under the optimistic climate-change projection, the number of days with Delta water temperatures above 77^{o}F was projected to double or triple, but under the pessimistic scenario, the number of such days increased exponentially, from about 20 per decade now to about 1000 per decade by end of century.

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 affected 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 helps to determine the extent to which upstream management is preventing climate change-driven trends to warmer waters in decades to come—a key factor in the status of the Delta as a habitat for endangered fish species like the Delta smelt.

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. Warming air temperatures over the Delta are expected to play a particularly important role in determining future water temperatures there, and recent projections have indicated that--in response to warming over the Delta--summertime water temperatures may rise by between 5^o and 11^oF by end of the 21^{st} Century (Wagner et al., 2011). 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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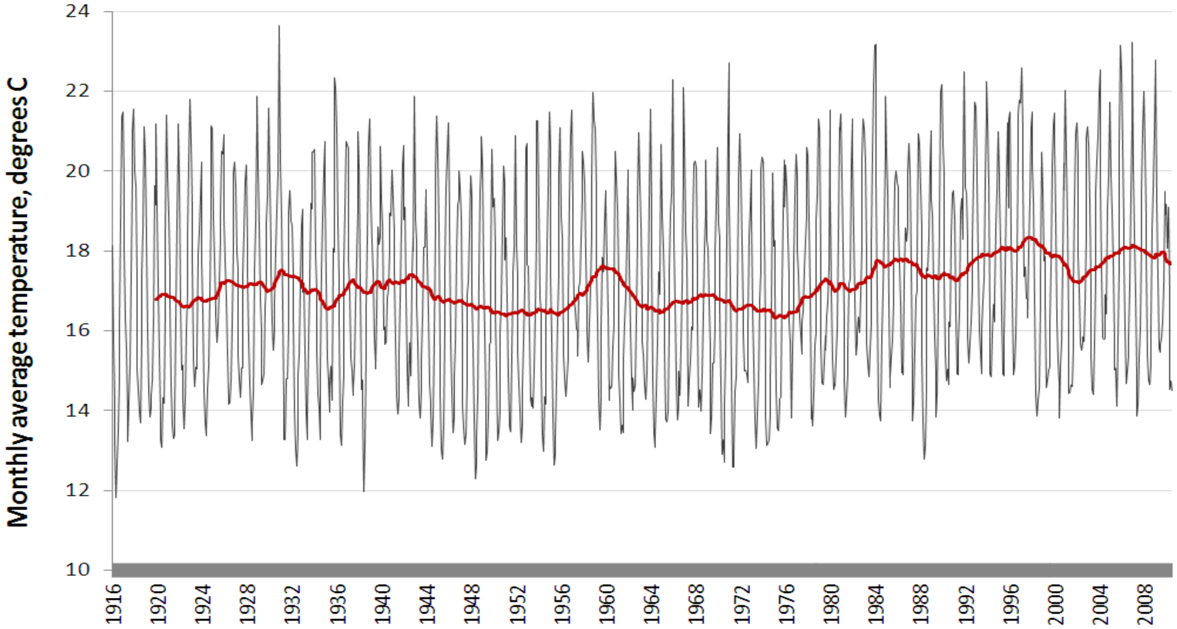
COASTAL OCEAN TEMPERATURE (UPDATED)

Like global ocean temperatures, California coastal temperatures have warmed over the past century.

Monthly Sea Surface Temperature: La Jolla, CA



Red line is 48-month moving average

Source: SIO, 2012

What is the indicator showing?

Sea surface temperature (SST) measured in La Jolla has increased by about 1°C since 1916, an annual warming rate of approximately 0.011^{o}C—about twice higher than the global average rate of warming of 0.006^{o}C/year over the last century (NCDC, 2005).

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 sea and land surface has increased by 0.74° C (+/- 0.18) over the last 100 years (IPCC, 2007e; NCDC, 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.

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 influences other factors, including transport and water column structure that affect populations.

Ocean observations (Levitus et al., 2001) and global climate models (IPCC, 2007e) 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 the "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 rate of warming at La Jolla 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. The Scripps SST time series is significantly correlated with SST records throughout the north Pacific (McGowan et al., 1998), so the interannual variability as well as long-term trend at Scripps is seen throughout the rest 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 et al., 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 extends back to 1916, making this the longest continuous record of its kind on the United States west coast and the Pacific Rim.

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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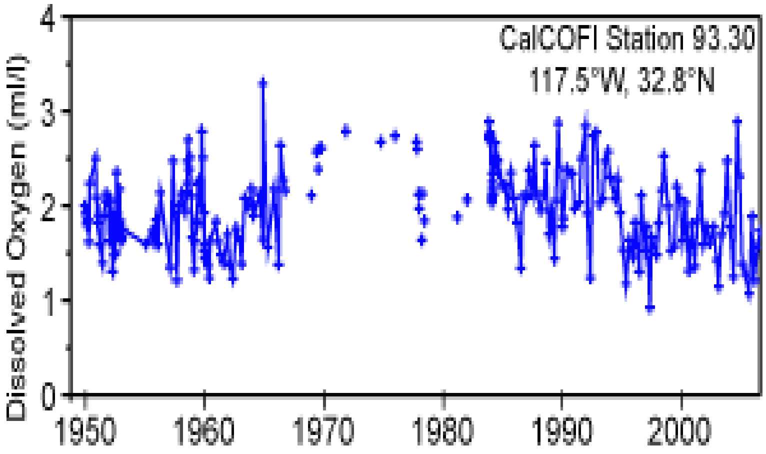
OXYGEN CONCENTRATIONS IN THE CALIFORNIA CURRENT (NO UPDATE)

TYPE II INDICATOR

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.

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).

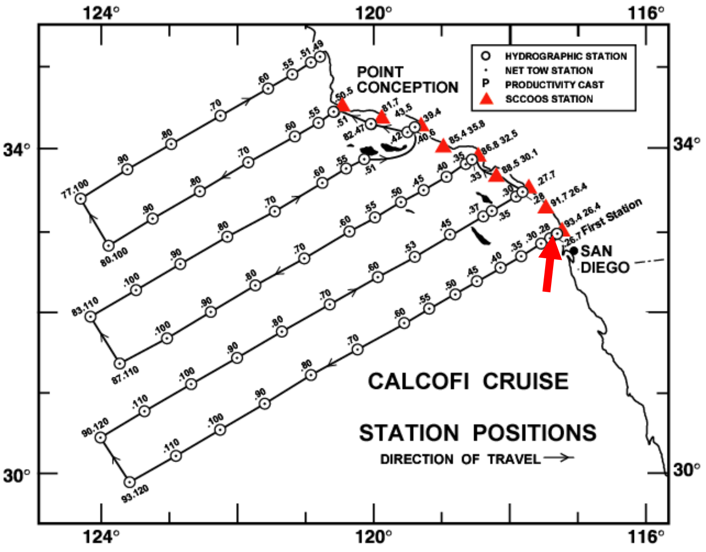
Dissolved oxygen levels off the coast of San Diego (at 200 m depth)



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.

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 on the right presents levels of dissolved oxygen at a location off the coast of San Diego, in the Southern California Bight (Station 93.30—see red arrow on the map, next page). The data are from sampling and monitoring conducted by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program. 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

Large declines in DO between 1984 and 2006 have been observed. The decrease 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., 2010). 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.

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IMPACTS 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. These include: poleward and elevational shifts in range; changes in the timing of growth stages (known as "phenology"); and changes in abundance of certain species and in community composition. Similar responses have been observed in studies of marine and freshwater species (IPCC, 2007f).

INDICATORS: IMPACTS ON BIOLOGICAL SYSTEMS

HUMANS

- Mosquito-borne diseases *(Type II) (updated information)*
- Heat-related mortality and morbidity *(Type II) (updated information)*
- Exposure to urban heat islands *(Type III) (new)*

VEGETATION

- Tree mortality *(updated information)*
- Large wildfires *(updated information)*
- Forest vegetation patterns *(no update)*
- Subalpine forest density *(new)*
- Vegetation distribution shifts *(new)*
- Alpine and subalpine plant changes *(Type II) (no update)*
- Wine grape bloom *(Type II) (updated information)*

ANIMALS

- Migratory bird arrivals *(no update)*
- Small mammal migration *(no update)*
- Spring flight of Central Valley butterflies *(updated)*
- Copepod populations *(updated)*
- Sacramento fall run Chinook salmon abundance *(new)*
- Cassin's auklet breeding success *(updated)*
- Shearwater and auklet populations off Southern California *(new)*
- Sea lion pup mortality and coastal strandings *(new)*

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MOSQUITO-BORNE DISEASES (UPDATED INFORMATION)

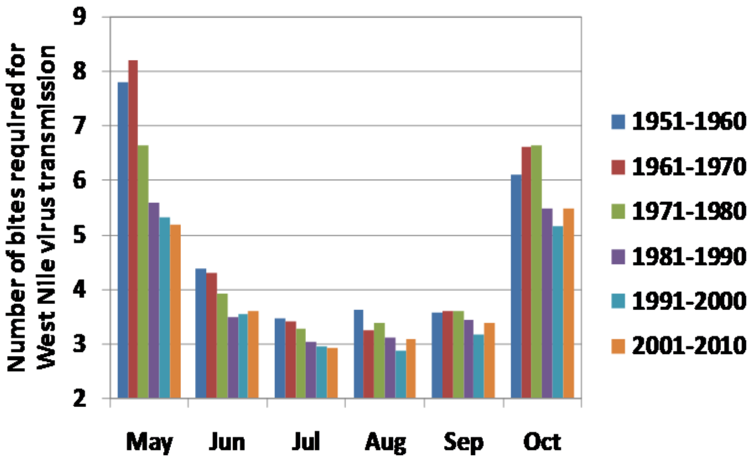
TYPE II INDICATOR

In California, most endemic arthropod-borne diseases are zoonoses (i.e., infectious diseases that are primarily transmitted in animals) caused by viruses, bacteria and other pathogens that are transmitted by arthropod vectors such as mosquitoes. Mosquitoes transmit disease agents among wild mammals and birds, with humans and domestic animals as incidental or spillover hosts. Warming temperatures are likely to increase the abundance of vectors in time and space, and therefore 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 supporting changes in the distribution and incidence of vector-borne diseases is less clear and confounded by changes in human-related factors such as landscape change (IPCC, 2007j).

California has maintained a comprehensive statewide mosquito and mosquito-borne encephalitis virus surveillance program for over 50 years. Mosquito abundance and infection are monitored by mosquito and vector control districts throughout the state. Of the twelve mosquito-borne viruses known to occur in California, western equine encephalomyelitis, St. Louis encephalitis, and West Nile viruses (WNV) cause human, veterinary and wildlife disease and are carefully monitored by health agencies (CDPH, 2010). For human disease surveillance, local mosquito control agencies rely on the detection and reporting of confirmed cases to plan emergency control and prevention activities. However, human cases of these mosquito-borne viruses are an insensitive surveillance measure because clinical cases are rarely diagnosed and most infected persons do not develop severe disease (CDPH, 2010). Early warning based on monitoring enzootic activity, i.e., the prevalence of infection among mosquitoes and birds, is needed for effective and timely preventive intervention.

Because interactions between mosquito and host populations depend upon ecological conditions, changes in climate may have a profound impact on the abundance of vectors (Reisen et al., 2008) and the transmission of mosquito-borne pathogens. The amount and pattern of available surface water due to precipitation or water management determine the quality and quantity of mosquito habitat as well as food for vertebrate host populations. Temperature impacts the rate of growth of mosquito populations, virus development in the mosquito, the frequency of blood feeding (host contact) and hence the frequency of transmission and risk of outbreaks. The potential impacts of long-term warming trends include the extended geographic range of mosquito populations, the elongation of the transmission season, and the enhanced rate of pathogen transmission.

A useful measure of the efficiency of transmission of a vector-borne pathogen is the number of bites or blood meals required by the vector before the pathogen can be transmitted. Investigators have studied the efficiency of transmission of mosquito-borne pathogens when mosquitoes were incubated at different temperatures (Reisen et al., 1992). They report that with increasing temperatures, fewer bloodmeals are required for transmission and there is a higher probability that the virus can be transmitted within a mosquito's lifetime. Similar data have been used to delineate the effective global distribution of different malaria parasites (Detinova, 1962) and how climate change may have altered this pattern (Chaves and Koenraadt, 2010; Parham and Michael, 2010). As shown in the graph on the left, the number of bites estimated for virus transmission in San Jose, California has declined throughout the transmission season, with the greatest changes having occurred during spring. During the past 6 decades, even in this relatively cool and marginally suitable WNV habitat, warming has decreased the estimated number of bites required for virus transmission and thus increase the potential for WNV transmission in this area. This is important because spring is a pivotal period of amplification for WNV and other mosquito-borne pathogens that strongly influences the potential for transmission to humans.



Number of bites required for a mosquito to begin transmitting WNV following infection estimated as a function of decadal mean temperatures for San Jose, California.

Researchers continue to explore whether climate change may be affecting the epidemiology of mosquito-borne viruses in California and how public health and vector control agencies can respond to these changes. Changes in temperature and precipitation are likely to cause changes both in geographic distribution and the abundance of vectors that carry human disease (CNRA, 2009). Expected shifts of late winter precipitation from snow to rain at high elevations (Cayan et al., 2008) will limit water storage and cause spring runoff to occur earlier and faster, which would result in increased mosquito habitat during wet years. The Asian tiger mosquito, an exotic container-breeding species that can transmit dengue and chikungunya viruses, has been discovered recently in Los Angeles County (ProMED-mail 2011), and increases in humidity or rainfall could increase the risk that such vectors will become established in California. Finally, projected increases in extreme climate events, such as heat waves, suggest that there may be greater risk of mosquito-borne disease, though the risk will also depend on the effectiveness of mosquito control programs (USGCRP, 2009).

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HEAT-RELATED MORTALITY AND MORBIDITY (UPDATED INFORMATION)

TYPE II INDICATOR

Heat-related illness is a broad spectrum of disease, from mild heat cramps to severe, life-threatening heat stroke, to death. The elderly, infants and young children, persons with advanced cardiovascular disease (myocardial infarction, congestive heart failure, and ischemic heart disease), and African-Americans have been found to be at increased risk from heat, specifically for mortality (Basu and Ostro, 2008a). Outdoor workers (e.g., firefighters and farmworkers), socially isolated populations, the poor and the medically underserved are also more vulnerable to the effects of heat than the general population (CDPH, 2007). Heat waves have long been known to cause illnesses and deaths, which are largely preventable. Early warning and surveillance systems, access to air conditioning, and public outreach and education are some measures that may prevent heat-related illnesses and deaths during heat waves.

Increasing trends in air temperatures and summertime temperature extremes in California over the past century (see *Annual Air Temperature* and *Extreme Heat Events* indicator, page 37 and 48) are expected to continue. In the next few decades, average temperatures are predicted to rise between 1 and 2.3 degrees Fahrenheit (^{o} F), rising between 3 and 10.5^{o}F by the end of the century. Further, the number of days of summertime extreme heat is 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 (CEC, 2006). Predicted increases in the frequency and duration of heat waves are expected to result in a greater public health burden from heat-related mortality and morbidity (IPCC, 2007f; Anderson and Bell, 2011).

Investigators worldwide have documented relationships between elevated ambient temperature and mortality (Basu, 2009; Anderson and Bell, 2011). Recent California studies suggest increased mortality risk not only with extreme heat, but also with increasing ambient temperature (Basu and Ostro, 2008a; Basu et al., 2008b; Basu and Malig, 2011). Until recently, little research and data have been available on illnesses or morbidity associated with heat exposures (English et al., 2009; Basu 2009).

Although both meteorological and health outcomes data are presently available, no reliable indicators showing trends in heat-related mortality and morbidity over time can be presented (hence the classification as a “Type II” indicator). Existing data collection systems in the state do not fully capture the health impacts of heat exposure, as will be discussed below.

Heat-related Mortality

During the July 2006 heat wave--which was unprecedented in terms of magnitude and geographic extent—coroners reported approximately 140 deaths caused by hyperthermia (Margolis et al., 2008). Average apparent temperatures[2] ranged from 81°F to 100°F (Margolis et al., 2008; Knowlton et al., 2009). As is often the case, the number

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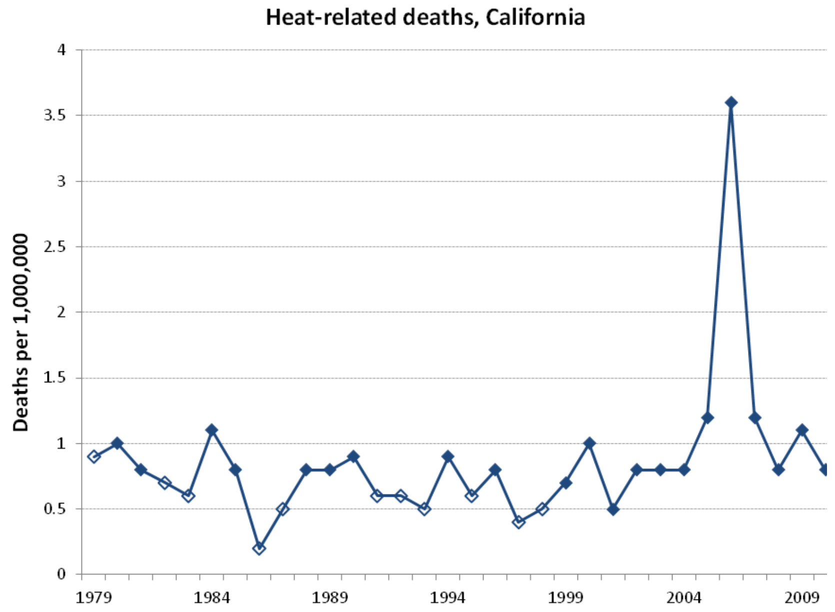
[2] “Apparent temperature" is a measure that reflects both temperature and humidity.

of heat-related deaths from the coroners' reports likely underestimates the full impact of the heat wave on mortality, as they rely on deaths that are coded as "heat-related" without any universal classification of these diseases. The true effect on mortality associated with the heat wave may have been up to three times higher than the 140 cases reported as heat-related; mortality increased by an estimated 9 percent per 10°F change in apparent temperature (Ostro et al., 2009) compared to 2.3 percent per 10°F change in apparent temperature during the warm season incorporating heat wave and non-heat wave periods (Basu et al., 2008).

Data for tracking trends in heat-related mortality are maintained by the U.S. Centers for Disease Control and Prevention (CDC) as part of a database of all deaths nationwide. In the CDC database, heat-related deaths include only those for which excessive natural heat is identified as the underlying cause of death on the death certificate.

The graph on the right presents annual heat-related death rates in California—that is, the number of deaths reported as having been caused by excessive heat for every 1,000,000 members of the state's population—for the past three decades. No conclusions can be drawn from the data, given the number of years with "unreliable" death rates; in addition, as discussed above, the reported values reflect the narrow definition of "heat-related" deaths. Heat is known to be a contributing factor in deaths among susceptible individuals with pre-existing conditions, such as cardiovascular or respiratory disease (Shen et al., 1998; English et al., 2009; Ostro et al., 2009). To better characterize trends in heat-related mortality, a broader definition of "heat-related" deaths has been suggested: one that includes deaths for which heat is listed as a contributing factor, in addition to those for which excessive heat is the primary cause of death (Shen et al., 1998; English et al., 2009). This would



Source: CDC, 2012; CDC, 2013

NOTE:

1) Graph shows deaths reported as caused by "excessive heat—hyperthermia" (classified as ICD-9 code E900), "due to weather conditions (code E900.0) for the years 1979 to 1998, and by "exposure to excessive natural heat—hyperthermia" (ICD-10 code X30) for 1999 to 2008.
2) Years with "unreliable" death rates (when the death count is less than 20) are shown with unfilled markers (diamonds).

include, for example, deaths due to heart failure or respiratory illness, with heat illness as a contributing factor (English et al., 2009; EPA, 2010).

Outside of heat waves or extreme heat events, recent analyses in California found mortality to increase with increasing apparent temperature (Basu et al., 2008b). Deaths from non-accidental causes increased by approximately 2.6 percent for every 10^o F increase in mean daily apparent temperature. These effects were found to be independent of criteria air pollutants, such as ozone, fine particulate matter, nitrogen dioxide, and carbon monoxide, and no significant pattern of effect modification was observed between apparent temperature and any air pollutant considered (Basu et al., 2008b). The effect was found to be acute, with same-day effects being most significant, supporting the notion that public health response to heat-related mortality should be immediate. Investigators considered the possible influence of mortality displacement, in which heat exposure would affect frail, elderly individuals, who would have died within a few days (Basu and Malig, 2011). They reported that the effect of apparent temperature on mortality had short-term as well as longer-term effects that affected a broader population, and therefore, has the potential for greater public health risk.

Heat-related Morbidity

Morbidity studies of heat waves in California are limited to the 2006 heat wave. Dramatic increases across a wide range of illnesses were observed, with over 16,000 excess emergency department visits due to heat-related illnesses (e.g., heat stroke, electrolyte imbalance, acute renal failure, kidney disease, diabetes and cardiovascular diseases) (Knowlton et al., 2009). The highest risk of heat-related illness was found in the usually cooler Central Coast counties, rather than in the Central Valley where the highest temperatures were recorded, indicating the role of population acclimatization and adaptive capacity (such as access to cool indoor environments) (CDPH, 2008).

Other notable studies using California data have found significantly increased risk of hospitalizations for multiple diseases, including cardiovascular disease, ischemic heart disease, ischemic stroke, respiratory disease, pneumonia, dehydration, heat stroke, diabetes, and acute renal failure to be associated with a 10^oF increase in same-day apparent temperature (Green et al., 2010). The use of air conditioning significantly reduced the impact of temperature on these health outcomes, although they still remained significant (Ostro et al., 2010). These outcomes, in addition to hypotension, intestinal infection, and heat illness were also found to be associated with emergency room visits, and effect modifications by race/ethnic group and age were observed for several outcomes (Basu et al., 2012). Apparent temperature was also found to be associated with preterm delivery, regardless of maternal racial/ethnic group, age, education, or sex of the infant (Basu et al., 2010). An increase in average weekly temperature the week before preterm delivery was found to cause the most profound effects, indicating a need for quick measures to mitigate exposure to heat.

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EXPOSURE TO URBAN HEAT ISLANDS (NEW)

TYPE III INDICATOR

Absorption of heat by dark paved surfaces and buildings, lack of vegetation and trees, heat emitted from buildings, vehicles and air conditioners, and reduced air flow around buildings can raise air temperatures in cities over the surrounding suburban and rural areas by 2 to 10°F (CCSP, 2008). This is commonly referred to as the "urban heat island" effect. During heat waves, urban heat islands are especially dangerous because they are hotter during the day and do not cool down at night, increasing the risk of heat-related illness for residents (CNRA, 2009).

Because low-income urban residents and communities of color are often segregated in the inner city, they are more likely to experience higher temperatures than suburban or rural residents. Analyses of neighborhoods in the Los Angeles, Sacramento, San Diego and San Francisco metropolitan areas found that increasingly greater proportions of households below the poverty line reside in neighborhoods with increasing impervious cover and decreasing tree canopy; the same relationships were found between the percentage of people of color in a neighborhood and both impervious cover and tree canopy (Morello-Frosch et al., 2009).

Exposures to urban heat are important for public health and social services agencies to consider in planning and implementing responses to heat emergencies. Indicators that identify urban heat islands can inform the development of mitigation measures. Many of these measures can result in multiple benefits beyond urban heat reduction such as reducing energy demand for heating and cooling; reducing stormwater runoff; and improving aesthetic qualities and increasing property values. Examples of mitigation strategies include planting trees and other vegetation, and installing cool roofs and cool pavements.

The amount of impervious surface in urban areas can be used as an indicator of heat island potential in California. Identifying areas where heat-absorbing surfaces and buildings with little vegetation or tree canopy are concentrated can reveal neighborhoods where temperatures will likely be amplified during heat events. For example, the thermal infrared photograph of the downtown Sacramento area (left image, below) shows red and yellow "hot spots" that generally correspond to concrete

Source: NASA, 1998

Source: Google Maps, 2010

areas or rooftops; blue and green areas correspond to cooler vegetative areas or water. A satellite view (image on the right, preceding page) is shown for reference. This information can help guide planning, mitigation and response efforts.

An indicator for tracking urban heat exposures will need to integrate data for multiple components: impervious surfaces; vegetation cover or tree canopy; and temperature. Community-level temperature data can be derived from thermal infrared images or collected using climate monitors at appropriate locations. At present, infrared images of California cities are not routinely taken, and climate monitors are often located only at airports, commercial buildings, and other non-residential locations.

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TREE MORTALITY (UPDATED INFORMATION)

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

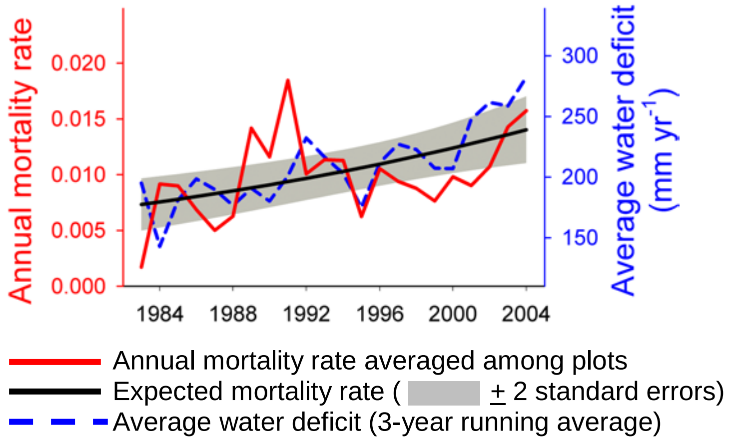
> *The 2009 climate change indicators report presented a tree mortality indicator which showed that deaths in the Sierra Nevada during 1982-2004 coincide with a temperature-driven increase in water deficit, a measure of drought. New data extending to 2007 show a similar increase in tree mortality in California and evidence of increased tree mortality in forests across the western United States (see below).*

An increase in the tree mortality rate, similar to that observed previously, was found using an updated and extended data set that encompasses the years 1982 to 2007. This data set also included three additional study plots in the southern Cascade Mountains in northern California, broadening the results beyond the Sierra Nevada.

Confidence that this trend might be present in other California forests is strengthened by the finding of rapidly increasing tree mortality rates in unmanaged old forests across the western United States. At this subcontinental scale, increases were pervasive across forest types, elevations, tree sizes, dominant genera, and past fire histories. Regional warming and consequent increases in drought stress were likely contributors to the widespread increases in tree mortality rates. Increased competition due to crowding and mortality solely due to aging of large trees were ruled out as possible causes of the increased mortality rates (van Mantgem et al., 2009).

The discussion of the tree mortality indicator from the 2009 report is reproduced below

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 (production of organic compounds from carbon dioxide) 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 50 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 and Stephenson (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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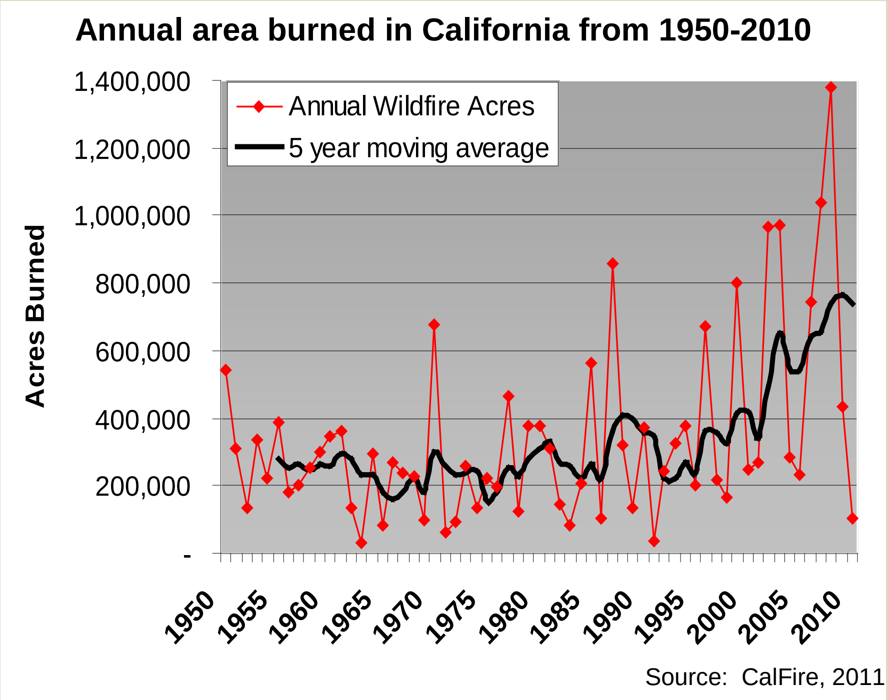
LARGE WILDFIRES (UPDATED INFORMATION)

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

> *The 2009 climate change indicators report presented wildfire frequency and other metrics describing large wildfires in the western United States. Here, California-specific data on wildfires are discussed.*

California is one of the most complex, wildfire-prone and fire-adapted landscapes in the world. Prior to the arrival of European settlers, natural wildfires shaped the structure and function of the state's wildlands, with an estimated 4.5 to 12 million acres burning annually. This pattern changed dramatically as a result, in part, of post-settlement land use practices such as agriculture, grazing, logging and mining—changes that were further magnified by modern era land use practices and organized fire suppression (CalFire, 2010).

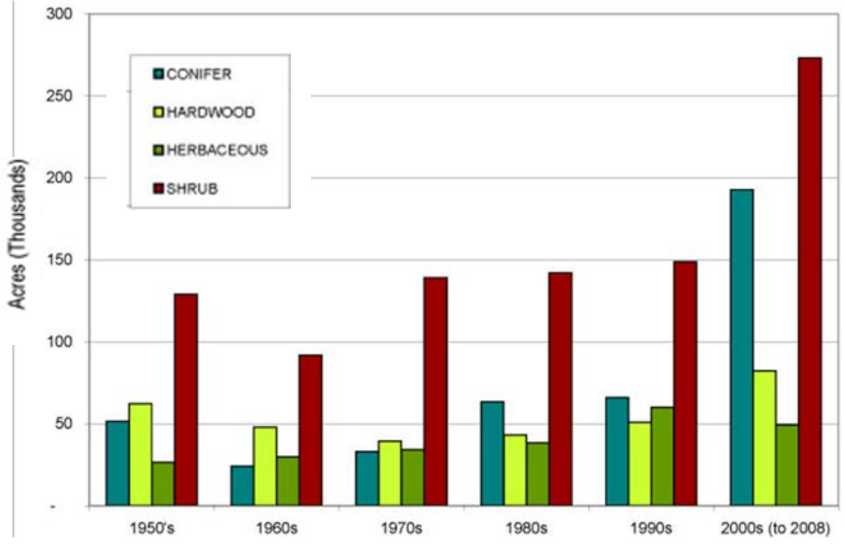


Source: CalFire, 2011

The graph on the right is based on data collected by the California Department of Forestry and Fire Protection (Cal Fire). The total area burned annually ranged from a low of 31,000 acres in 1963 to a high of 1.4 million acres in 2008. High annual variation—largely attributed to weather conditions and lightning events that result in dispersed ignitions in remote locations—makes it difficult to determine long-term trends (CalFire, 2010). However, the data suggest a trend toward increasing acres burned statewide—a pattern supported by the fact that the three largest fire years since 1950 have occurred since 2000 (2003, 2007 and 2008). In addition, the annual average since 2000 is 598,000 acres, almost twice the annual average for the 1950-2000 period (264,000 acres).

These trends are likewise evident when fire acreage data are organized by decade, as in the graph on the right. A large spike in annual average acreage of conifer and shrubland burned occurred in the most recent decade.

Annual average acres burned by decade by vegetation type



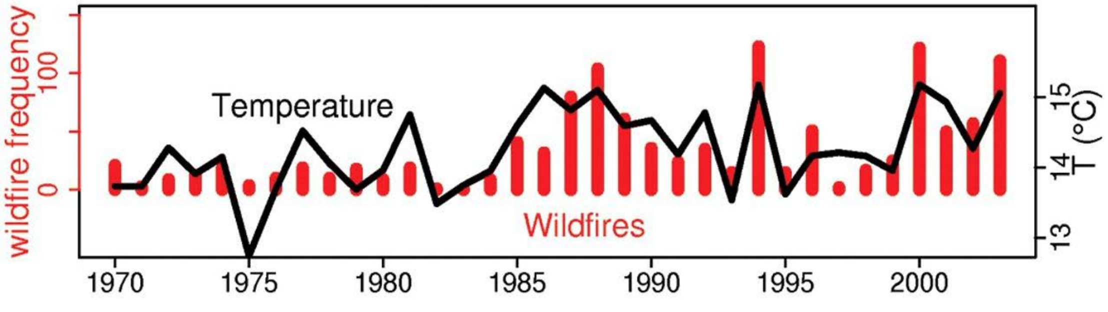
Source: CalFire. 2010

The size, severity, duration and frequency of fires are greatly influenced by climate. California's fire season seems to be starting sooner and lasting longer, with climate change suspected as a key mechanism for the change. Warmer spring and summer temperatures, reduced snowpack and earlier spring snowmelt, and increased frequency of Santa Ana conditions have been identified as factors that have influenced the increase in wildfires.

Research suggests that large fires and burned acreage will increase throughout the century, with some declines after mid-century due to vegetation-type conversions (CalFire, 2010).

The discussion of the large wildfires indicator from the 2009 report is reproduced below.

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



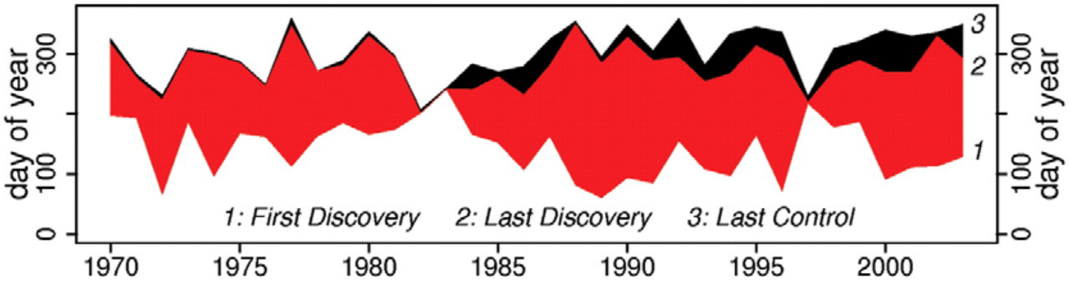
Source: Westerling et al., 2006

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 (see graph below).

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



Source: Westerling et al., 2006

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).

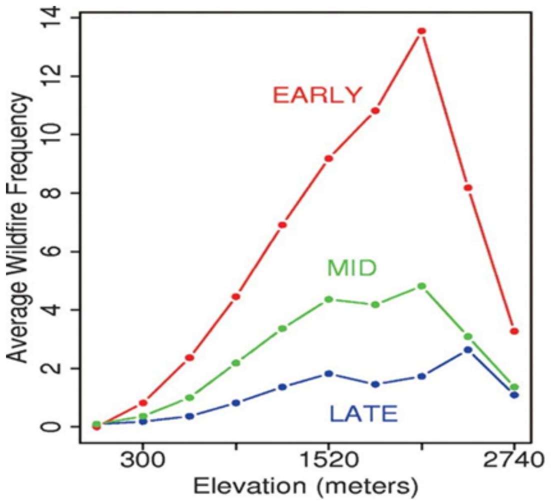
Wildfires have caused concern in recent years due to the severity and expanse of the areas they have consumed, including hundreds of homes burned and devastating damage to natural resources. Modeling of wildfires in California predicts that the largest changes in property damage will occur in wildland/urban 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.

Forest Wildfire Frequency and the Timing of Spring Snowmelt**



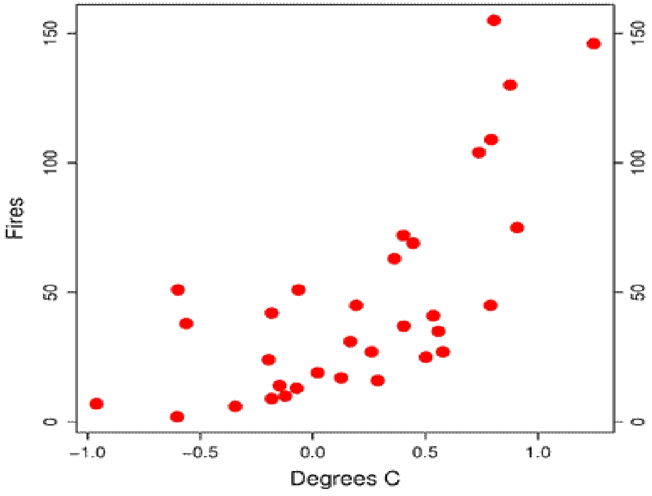
Source: Westerling et al., 2006

** “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).

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.

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 below).

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



Source: Westerling and Bryant, 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 activity. Therefore, early springs and dry summers tend to increase the likelihood 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 activity 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 and Bryant, 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, Savage 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 (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 the date when the last large fire is declared under control.

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FOREST VEGETATION PATTERNS (NO UPDATE)

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

Figure 1

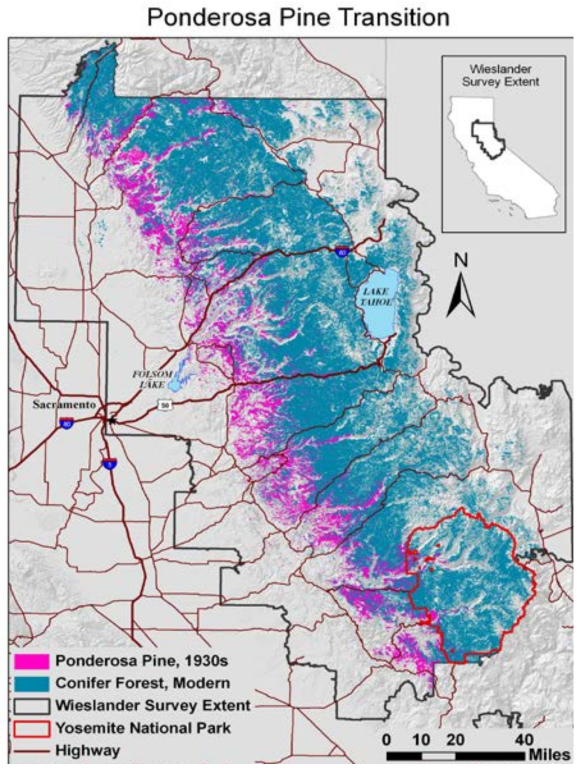
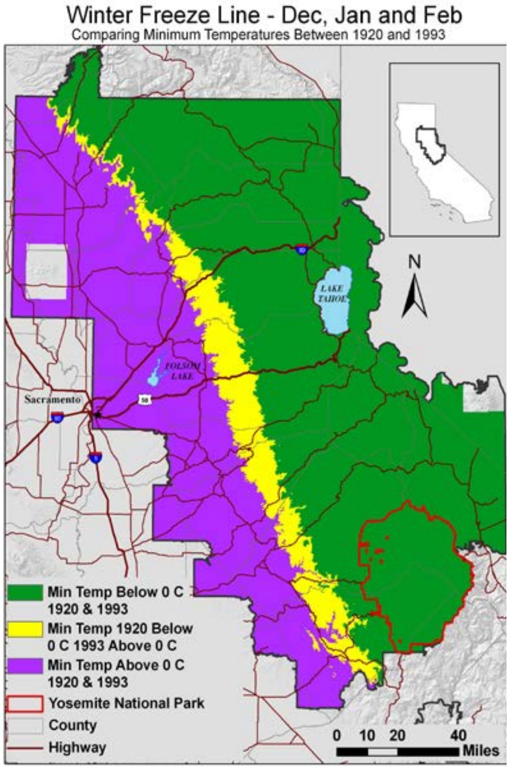


Figure 2



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 had freezing temperatures 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 has freezing temperatures 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. The discovery of a new set of tree seedlings, recently established in alpine areas above the tree line, 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 that are experiencing a warming of winter nights. On average, these areas used to have freezing temperatures 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. This has been 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 resistant 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, Hidalgo 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; Wieslander, 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, 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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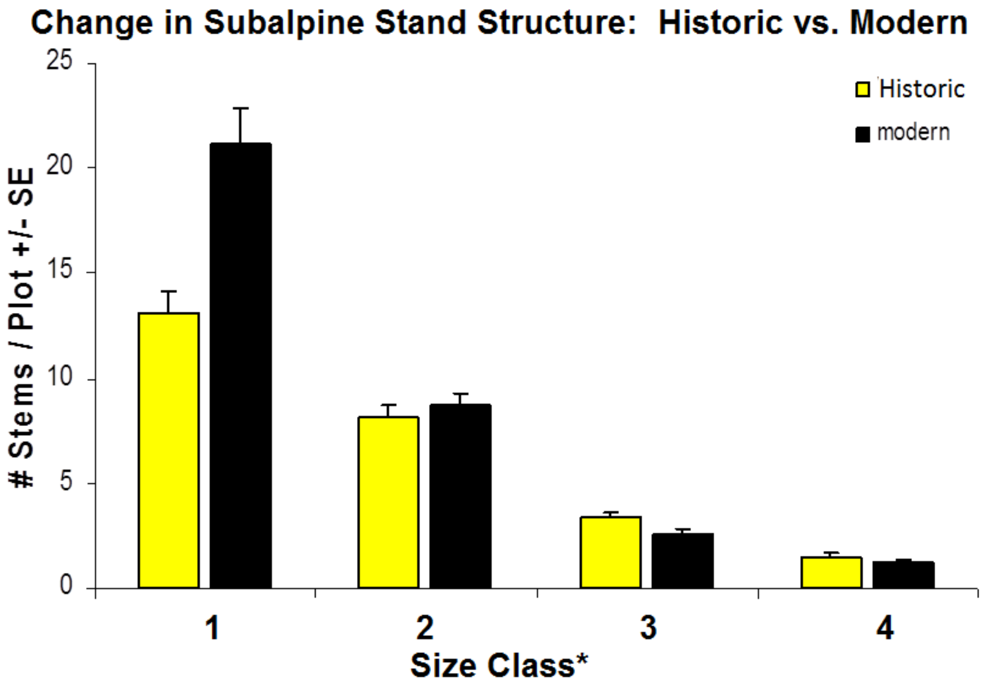
SUBALPINE FOREST DENSITY (NEW)

Subalpine forests in the Sierra Nevada are much denser today than they were over 70 years ago



Historic = vegetation type mapping (VTM), sampling from 1929-1934
Modern = sampling from 2007-2009

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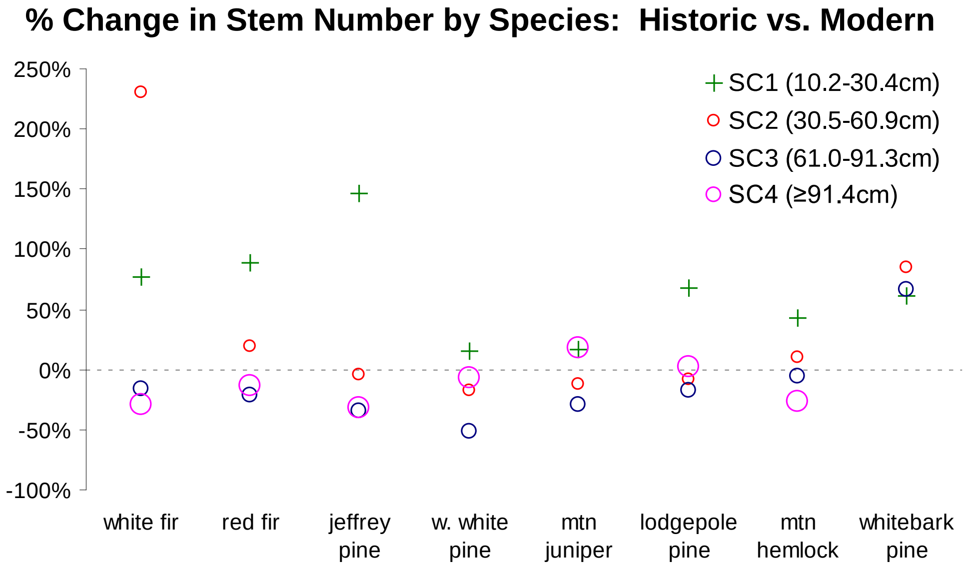
*Size Class (SC) is based on tree diameter at breast height (dbh), as follows:

SC1: 10.2 – 30.4 cm;	**SC2**: 30.5 – 60.9 cm;	**SC3**: 61.0 – 91.3 cm;	**SC4**: ≥ 91.4
(4 -12 inches)	(12 - 24 inches)	(24 - 35.9 inches)	(≥ 36 inches)

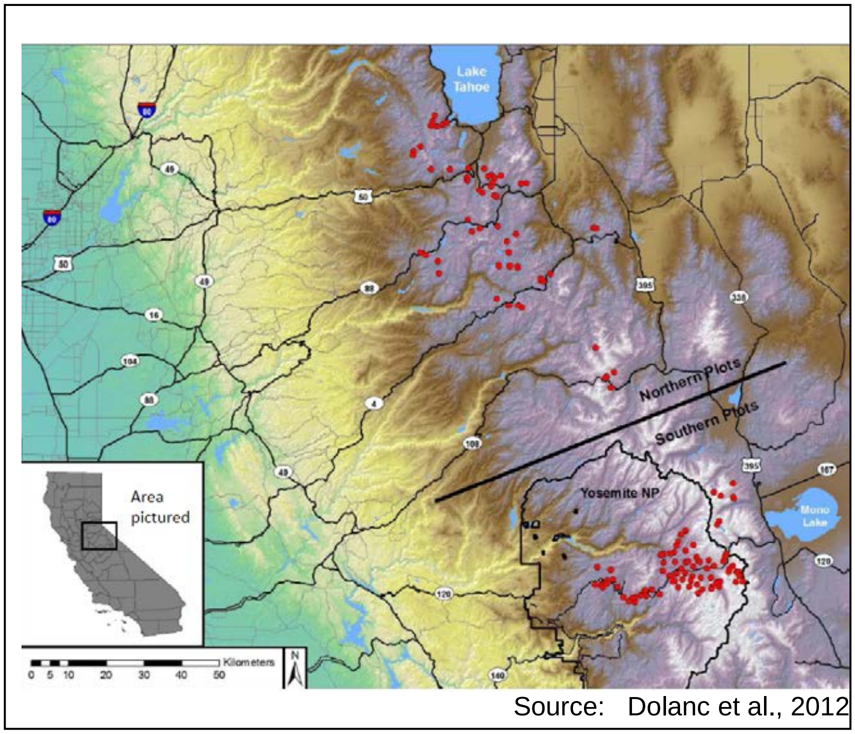
Source: Dolanc, 2012



Source: Dolanc et al., 2012

What is the indicator showing?

The structure of subalpine forests shifted so that there are now many more small trees [those categorized as SC1, having diameters measuring 10.2-30.4 centimeters (cm) at breast height (that is, a height of 4.5 feet)] and fewer large trees (those categorized as SC-3 and SC-4, having diameters ≥61.0 cm), compared to about 75 years ago. Small trees have increased by 62 percent while large trees have decreased by 21 percent; that results in a net of 30 percent more stems present today than historically. These shifts are ubiquitous throughout the subalpine zone (2300-3400 meters (m) or 7,546 -11,155 feet elevation) of the central Sierra Nevada (see map, right), and have occurred to a surprisingly consistent degree for the eight most common tree species native to this zone. These shifts are likely driven by regional climatic changes that occurred over the same period, causing the growing season to lengthen. Interestingly, no apparent change in the relative abundance of tree species were observed.



Source: Dolanc et al., 2012

Why is this indicator important?

Such large-scale shifts in forest structure could have detrimental effects on the ecological processes of the subalpine region. Historically, fire has not played a major role in Sierran subalpine forests. Though much of California's vegetation is adapted to frequent fire, fire in the subalpine zone has historically been infrequent and isolated (Wagtendonk and Fites-Kaufman, 2006). Stand structure of subalpine has historically been sparse, with shallow fuel beds insufficient to carry a fire very far. However, an infilling of these stands will naturally lead to increased dead and live fuel and could ultimately lead to larger and more frequent fire. Since most species native to subalpine are not adapted to fire, this has the potential to shift dominance of subalpine toward lower-elevation, fire-adapted species, effectively catalyzing an upward shift of ecological zones.

Densification of subalpine forests and warming temperatures could also tip the scales in favor of insect outbreaks and disease. Beetle infestations have caused widespread mortality in high-elevation forests in the Pacific Northwest and Rocky Mountain regions, including two species present in Sierran subalpine, lodgepole pine and whitebark pine. These infestations were linked to changing climate and forest conditions that are conducive to the beetle's life cycle (Kurz et al., 2008). Increased density of Sierran subalpine forests and warming temperatures should each lead to increased tree mortality and conditions ripe for outbreaks in the Sierra Nevada.

A similar situation exists for white-pine blister rust, which affects 5-needle pines throughout the western mountains, including western white pine and whitebark pine, two species found in Sierran subalpine (Tomback and Achuff, 2010). Like beetle outbreaks, so far the impact of this disease in the Sierra Nevada has been minimal, but it does exist, and a densification of forest could cause widespread mortality. Devastating beetle outbreaks and/or disease could lead to a compositional shift, in favor of species more resistant to these pathogens. In addition to these potential negative effects, major shifts in composition and structure to an ecosystem are likely to lead to numerous other, unforeseen biological changes in the ecosystem.

What factors influence this indicator?

Although forest stand structure has become more strongly skewed toward younger size classes, the relative abundances of the different tree species have not changed appreciably and there is no evidence of lower elevation species replacing higher elevation species. The pattern of nearly ubiquitous change is indicative of factors that are operating with strong influence and at regional, rather than stand-level scale. Over the same time period that structural shifts took place, temperatures in the same region rose by an average of 1.4 °C for night-time lows and 0.4 °C for daily highs. Precipitation was also slightly higher. The winter snowpack in the Sierra Nevada is melting sooner (Kapnick and Hall, 2010) and the proportion of rain to snow is increasing (Knowles et al., 2006).

These changing conditions have led to longer growing seasons which should allow for increased survival and recruitment of small trees in the subalpine. At the same time, as other studies have shown, increasing temperatures should also lead to higher mortality of large trees.

Increasing concentration of nitrogen may also be contributing to densification of small trees. Increased deposition of nitrogen from pollution sources upwind has been documented in the Lake Tahoe Basin. However, because nitrogen deposition is highly contingent upon the location of pollution sources, its effects are highly variable across the landscape (Fenn et al., 2003) and therefore not likely to account for the rather consistent and widespread shift in subalpine structure. It has also been suggested that higher concentrations of carbon dioxide could cause major structural shifts, but research has shown that this is unlikely to happen in high-elevation forests (Grace et al., 2002).

Though fire suppression has caused similar shifts (i.e., a densification of the forest by small trees) at lower elevations, the historic low frequency of fire in the subalpine suggests that 20th century fire suppression did not have much of an impact on these forests. Other researchers have concluded that the cessation of sheep grazing on public lands over 100 years ago led to increases in density of subalpine trees.

However, while this could explain increases of lodgepole pine near meadows, it is not sufficient to explain the widespread, multiple-species responses seen in this indicator.

Technical Considerations

Data Characteristics

Plots of approximately 809 m^2 (8712 ft^2) were originally sampled from 1929-1934 as part of the Wieslander Vegetation Type Mapping (VTM) project that represented the US Forest Service's original forest inventory in California (Wieslander et al., 1933). From 2007-2009, 139 historic vegetation plots were resampled throughout wilderness areas at 2300-3400 m elevation in the central Sierra Nevada. Care was taken to sample modern stand conditions with a protocol compatible with the original surveys, matching plot size, shape and orientation as closely as possible. Nearly half of the 139 plots were concentrated in the Tioga Pass area of Yosemite National Park, with the other half coming from passes further north, as far north as the Desolation Wilderness; the study area encompasses approximately 5500 km^2.

Four typical subalpine forest stands

Source: Dolanc et al., 2012

Analysis was centered on differences between numbers of stems in historic VTM versus modern stands, using the four size-class dbh (diameter at breast height) categories set by the VTM team (SC1, SC2, SC3, and SC4). Comparisons were made for all species combined as well as each of the eight most-common tree species.

To determine change in climate over the same time period, data from two weather stations at either end of the study area, Tahoe City in the north and Huntington Lake in the south, were accessed. 30-year means were calculated for 1916-1945 and 1976-2005, representing the historic and modern periods influencing each of the sample periods in the vegetation data. Differences in climate between the two time periods were calculated for annual minimum temperature, annual maximum temperature and annual precipitation. Differences in these variables during the July through September growing season were also calculated.

Strengths and Limitations of the Data

The strong structural shifts observed from subalpine of the Sierra Nevada are the first empirical-based observations of such widespread shifts. Many other studies have made similar observations using repeat photography or comparison of VTM data with a different set of modern field data. However, this is the first re-sampling effort focused on such changes over a large region of the Sierra Nevada.

Using VTM data as historic reference has been criticized because VTM field crews did not permanently mark their plots, meaning precise relocation of plots is not possible. However, it is possible to navigate to the same slope facet and likely the same forest stand using their data on canopy composition, elevation, slope, aspect and several other environmental variables. As long as many locations are resampled, this approach should be sufficient and preferable to studies that use entirely different sets of modern data for comparison with VTM conditions. With resampling, differences between each pair of historic vs. modern plots have been minimized. Because of these considerations, the analysis for this study is focused on overall change (all 139 plots combined). The modern resampling effort covered a large region, with a large sample size. Numerous recent papers have used the VTM data set as a historic reference and it appears as though this trend will continue.

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VEGETATION DISTRIBUTION SHIFTS (NEW)

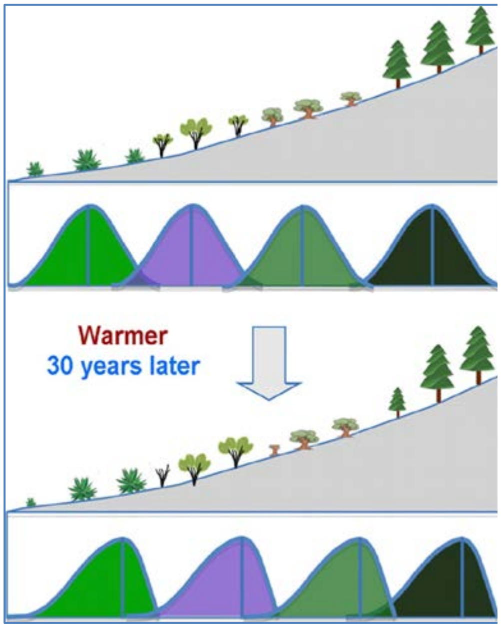
The distribution of vegetation across the north slope of Deep Canyon in the Santa Rosa Mountains has moved upward 213 feet in the past 30 years.

Change in mean elevation* of plant species in the Deep Canyon Transect

	Mean elevation, m		
Common Name	**1977**	**2006-2007**	**Change**
White Fir	2,421	2,518	96
Jeffrey Pine	2,240	2,267	28
Canyon Live Oak	1,987	2,033	47
Sugar Bush	1,457	1,518	61
Desert Ceanothus	1,602	1,671	70
Muller's Scrub Oak	1,485	1,522	37
Creosote Bush	317	459	142
Burrobush	630	748	118
Brittlebush	574	674	100
Desert Agave	693	643	-50
Mean change in elevation **(213 ft)**			**65 m**
95% confidence interval (112 ft)			34 m

**Change in cover-weighted mean elevation of ten most widely distributed species in the Deep Canyon Transect*

A conceptual diagram of vegetation distribution shifts



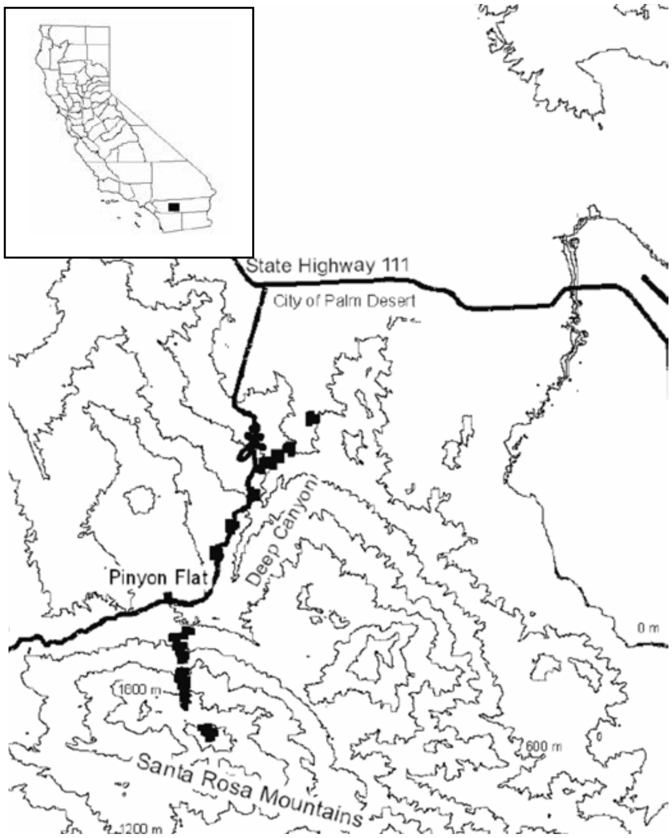
Source: Breshears et al., 2009

What is the indicator showing?

The mean elevation of nine of the ten dominant plant species in the Deep Canyon Transect of Southern California's Santa Rosa Mountains (see map, next page) have moved upslope in the past 30 years (Kelly and Goulden, 2008). A comparison of two vegetation surveys of plant cover—one in 1977 and the other in 2006-2007—along an 8,400-foot elevation gradient found that the average elevation of the dominant species rose by 65 meters (213 feet) between the surveys. All vegetation types moved upward, including small desert shrubs, chaparral, Canyon oak, and large conifers.

Although the species distribution moved upslope, the upper and lower range limits of these species have not changed. At the lower half of the species' ranges, individual plants have pruned limbs or completely died, reducing their dominance. An increase in cover was observed at the upper half of the species' ranges, where mature plants have reproduced and grown in size, increasing their dominance.

The conceptual diagram above illustrates these changes. Vegetation species along the mountain slope were distributed in a bell curve along the slope in 1977, with the highest



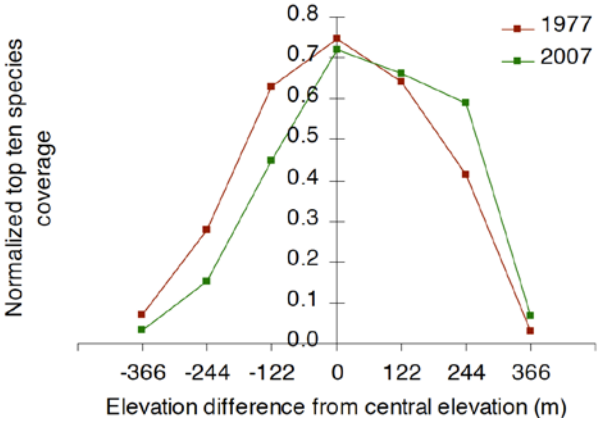
The sites of the Deep Canyon surveys and their location in California

abundances at the middle of each species' range. After 30 years of warming and drought, vegetation experienced die-off at the lower edges of each species' range, while plants at the cooler, wetter, upper elevations increased in dominance.

Vegetation distribution changes at Deep Canyon can be compared to the conceptual diagram using the graph below. A detailed discussion of the derivation of the metrics presented is beyond the scope of this narrative (see Kelly and Goulden, 2008 for details). In simple terms, the graph shows plant coverage (which represents the percent of ground surface covered by vegetation) plotted against elevation, with “0” representing the “center elevation” (the midpoint of the lowest and highest elevations where each species was found.)

(The y-axis of the graph shows “normalized” coverage, derived by dividing each species' coverage at each elevation in 2007 by its maximum coverage at any elevation in 1977 and averaging across the ten dominant species.) The graph shows that the ten dominant species in the survey area had a symmetric normalized distribution in 1977. This changed to an upwardly skewed distribution in 2007. From 1977 to 2007, cover declined in the lower parts of the species' original ranges (by a median of 46 percent) and increased in the upper parts of the original ranges (by 12 percent).

Vegetation distribution, ten dominant species at Deep Canyon



Source: Kelly and Goulden, 2008

Why is this indicator important?

Plant ranges are limited by environmental conditions. On a mountain slope, the climate of the lower extent of a species' range experiences warmer and drier conditions, while the upper extent of a species' range is cooler and wetter. Climate warming or drought is expected to increase stress on plants at lower elevations, pushing them upward into the cooler, wetter climates higher on the slope. Recent climate warming and drying has been found to be pushing conifers upslope across the Southwestern United States by killing the trees at the lower, warmer, drier edges of their ranges (Allen and Breshears, 1998; McDowell et al., 2010).

The climate and vegetation gradient of Deep Canyon's slopes is analogous to the south-to-north gradient of California. Deep Canyon's climate ranges from hot desert at the mountain base, stretching upward through warm chaparral, and finally into mild conifer forests at the mountain peak. This vegetation and climate gradient is similar to the transition along the state of California, from the southern deserts, northward through chaparral-covered foothills and mountains, and into the mild evergreen forests of northern California. Understanding the effects of local climate change on Deep Canyon's vegetation gradient will help to predict how California's vegetation will respond to a warmer or drier climate.

This indicator is consistent with biological range shifts seen around the globe (Chen et al., 2011). Plant, bird, mammal, and insect ranges are retreating away from the equator and up mountain slopes, generally tracking the temperature changes observed within each species' range. There is major uncertainty surrounding any individual species' ability to migrate in response to climate change. In Deep Canyon, no species were found outside their historic range. If species are not able to establish in new locations, this study might be revealing the beginning of a local extinction of each species and local ecosystem collapse.

What factors influence this indicator?

The climate of Deep Canyon has become warmer and drier in the past 30 years. Temperatures have increased 1.1 ^{0}F from 1977 to 2007, and droughts have intensified. The combination of warming and drying has effectively moved the climate zones of Deep Canyon upslope about 200 feet, similar to the amount the vegetation has shifted upslope.

The change in plant distribution observed in Deep Canyon may be attributed in part to a severe drought from 1999 to 2002. This drought caused marked vegetation mortality throughout Southern California, directly through drought stress and indirectly through insect attack, and many recently dead plants were observed during the survey. However, recent mortality alone cannot explain the elevation shifts. Many plants that had died before the 1999–2002 drought were also noted, as well as an increase in cover in the upper half of the species' ranges. These trends indicate that warming and/or drying of climate has been stressing the lower elevation plants and providing more favorable conditions for plants at higher elevations over the 30-year period.

These changes are consistent with predictions of the effects of climate warming and drought on mountain ecosystems.

Four considerations provide evidence that the observed vegetation redistribution is attributable to climate:

- Vegetation shifts were uniform across elevation, implying that the ultimate causal factor was uniformly distributed. Recent climatic trends in Southern California do not appear to vary strongly with elevation.

- The vegetation shifts are consistent with the expected bioclimatic effects of most of the observed climatic shifts. Increased temperature, longer frost-free period, increased elevation of the snow line, and occurrence of severe drought should increase plant stress in some years. This increased stress would be expected to decrease a species' ability to survive in the drier, warmer, lower parts of its range and increase its ability to survive in the wetter, cooler, upper parts of its range.

- The change from a symmetrical vegetation distribution to an upwardly skewed distribution (see graph, *Vegetation distribution, dominant species*), when averaged across species and elevation, can be interpreted as a sign of the impact of climate change on vegetation distribution.

- The vegetation shifts resulted in part from mortality during the 1987–1990 and 1999–2002 droughts. The connection between mortality and drought is consistent with a fingerprint of climate change.

Two alternative explanations for the vegetation redistribution, changes in fire frequency or air pollution, merit consideration. The wildfire regime in Southern California has changed over the last century, resulting in plant demographic shifts, especially in montane forest. However, the fire regime in Deep Canyon is similar to its historical norm, and fire effects would not produce uniform changes across the elevation gradient. Schwilk and Keeley (2012) claim that the upslope redistribution of one species in Deep Canyon, *Ceanothus greggii*, was due to elevational differences in historic fires and not by climate warming. However, observations of postfire recovery of *C. greggii* outlined in Zammit and Zedler (1993) support the conclusion that an influence stronger than fire history is redistributing Deep Canyon's dominant species upwards. Air pollution as an explanation is similarly problematic: ozone-related mortality is concentrated only at higher elevations, and would not produce the uniform changes that were observed across the elevation gradient.

The upward movement of the dominant species at Deep Canyon in just 30 years can also be attributed to recent changes in the local climate. The establishment of species at locations well above their previous ranges appears to have been minimal, and the observed upslope movement is a result of shifting dominance within existing communities, rather than the expansion of ranges to new elevations. The climate factor most influential on species redistribution could not be determined. In fact, the various observed climatic changes may interact and reinforce each other; climate warming coupled with increasing climate variability intensifies the effects of extreme yet unexceptional droughts.

The local changes could be caused by regional urban heat island effects or long-term climate fluctuations, such as the Pacific Decadal Oscillation. Nonetheless, the climate changes observed are similar to climate changes that have been predicted with or attributed to greenhouse gas-forced global climate change. The study results imply that surprisingly rapid shifts in the distribution of plants can be expected with climate change, at least in areas where seed dispersal is not a major constraint, and that global climate change may already be influencing the distribution of vegetation.

Additionally, the exact mechanisms of the plant mortality are unknown. How a tree dies in response to drought is a surprisingly difficult question that the scientific community continues to discuss (Waring, 1987; Breshears et al., 2009; van Mantgem et al., 2009). Drought and warming have caused forest mortality worldwide and no other plausible explanation for the vegetation shifts were observed.

Technical Considerations

Data Characteristics

This indicator is based on a re-survey of an initial vegetation study conducted in 1977 (Zabriskie, 1979). Zabriskie's survey consisted of 22 belt-transect surveys 400 yards long, at 400' elevation intervals, from 0' to 8400' elevation along the north face of the Santa Rosa Mountains. These surveys counted live perennial vegetation crossing the 400-yard transect and noted species and coverage amount.

The exact location of Zabriskie's original surveys is lost. The study investigators were able to relocate the surveys within 10-20 yards of the original location using the original selection criteria: north-facing slopes, with transects centered on north-facing ridgelines and following the 400' interval isocontour. Jan Zabriskie also toured the sites with the investigators to explain his original sampling strategy and point out original locations.

Strengths and Limitations of the Data

A common problem in revisiting historic studies is finding the exact location of the original sites. Discussion with Zabriskie, original maps, careful and consistent site location criteria, and a relatively small geographic area, provide confidence in the investigators' accuracy in relocating the original survey sites. Location inaccuracy is the largest source of uncertainty in the data. The vegetation coverage methodology was identical to Zabriskie's and could result in biases of less than a few percent per transect. Year-to-year fluctuations could be a problem in extrapolating one survey to a 30-year trend. A major strength of this survey is that the species evaluated in this survey are generally long-lived, thus the vegetation changes observed are the result of long-term trends and not short-term variability. Species in the survey such as yucca, white fir, creosote, and California lilac have lifespans of decades to centuries, and thus high mortality rates within 30 years are considered significant changes. Finally, weather station data do not come from within the survey site; the climate data come from nearby stations around the Southern California desert mountains.

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ALPINE AND SUBALPINE PLANT CHANGES (NO UPDATE)

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 et al., 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; Millar, 2006b).

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WINE GRAPE BLOOM (UPDATED INFORMATION)

TYPE II INDICATOR

Wine grapes are known to be highly sensitive to climatic conditions, especially temperature (IPCC, 2007j). 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).

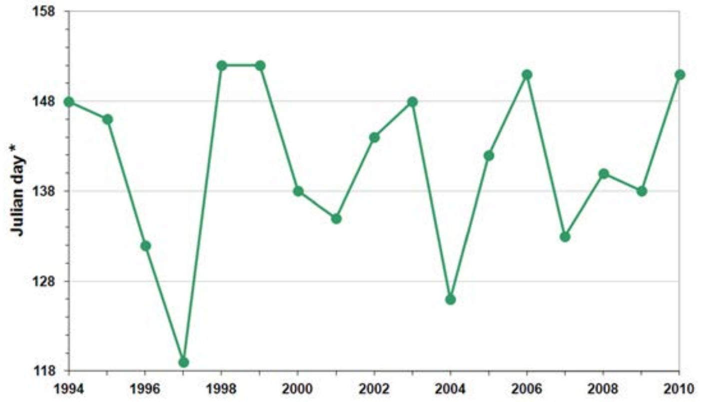
The climate sensitivity of wine grapes has made grape harvest dates a proxy to reconstruct climate in France back to the 1300s (Chuine et al., 2004). Grapevine phonological or developmental stages include bud break, flowering or bloom, fruit set, veraison (color change and beginning of maturation), harvest (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^{o}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^{o}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).

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 on the next page presents data on bloom dates for one grape variety in one vineyard in one region (Cayan et al., 2011). No trend is evident. Ongoing monitoring of bloom dates at this vineyard, along with data for other varieties and other wineries, will allow further characterization of wine grape development and climate-related trends in the region.

The data were among the phenological data evaluated in a recent study exploring the links between climate change and wine grape phenology and composition in the Napa Valley (Cayan et al., 2011). The region has experienced warming over the last several decades, particularly during the nighttime, and primarily from January through August at several of 30 weather stations. The study found that antecedent weather and climate significantly influenced the timing of phenological stages. Phenological stages were generally found to occur earlier with prior warm conditions. The study found relatively robust correlations between bloom, veraison and harvest, but weak correlations between any of these stages and budburst.

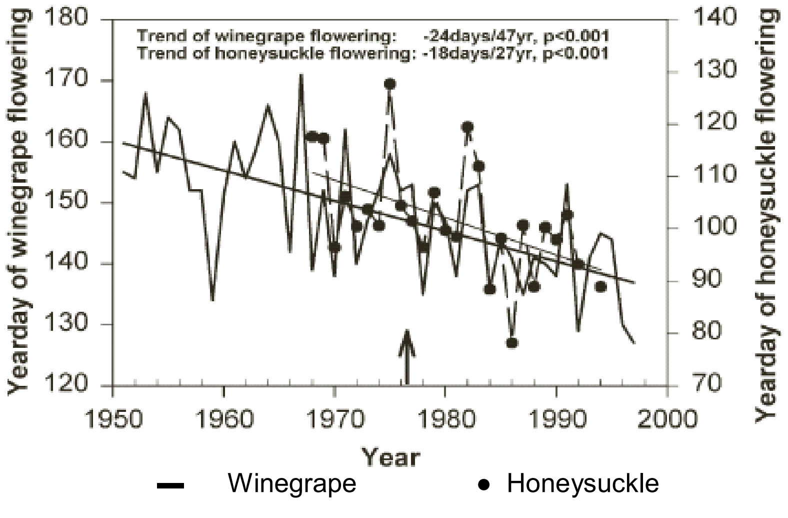

Pinot Noir Bloom
Saintsbury Home Ranch; Napa side of Carneros

Source: D. R. Cayan, K. Nicholas et al., 2011

** 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.

Estimated wine grape flower dates



Source: R. R. Nemani, M. A. White et al., 2001

The graph above shows a 24-day advancement of the estimated flowering dates between 1951 and 1997. (Also shown are observed honeysuckle flowering dates from four sites in the Napa and Sonoma Valley regions 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.

The production of high quality wine grapes is expected to benefit from a warmer climate because of a longer growing season and more favorable growing conditions. However, continued warming may, in the future, reach a point where growing certain wine grape varieties may no longer be viable (CNRA, 2009). These changes could be economically devastating for California, the state that produces 90 percent of all wines in the United States, and the world's fourth leading wine producer (WI, 2011).

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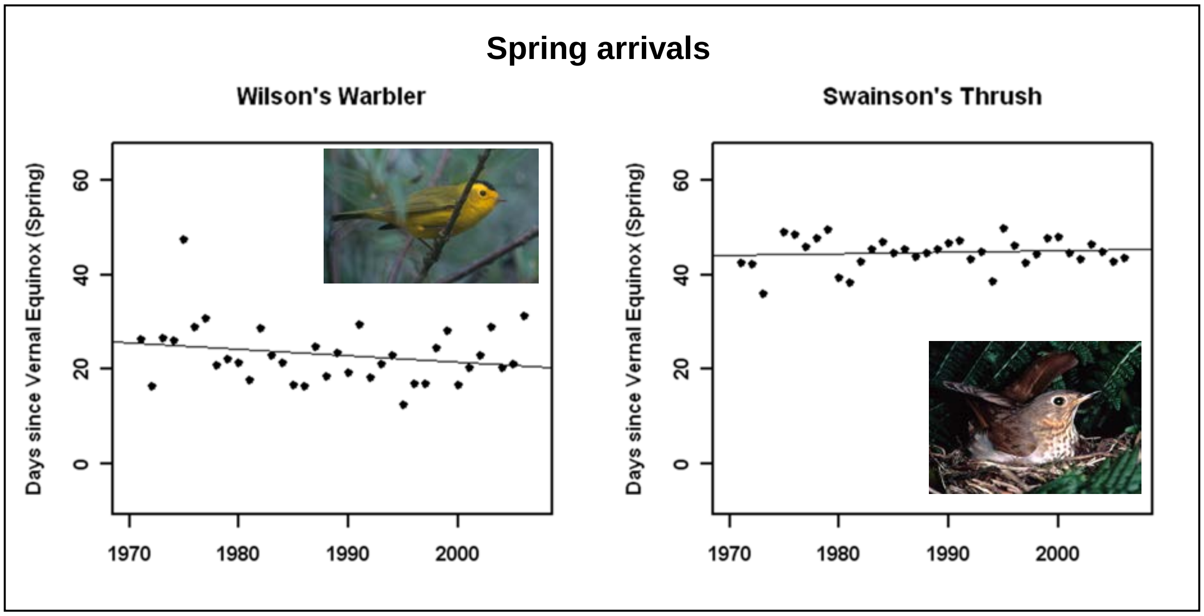
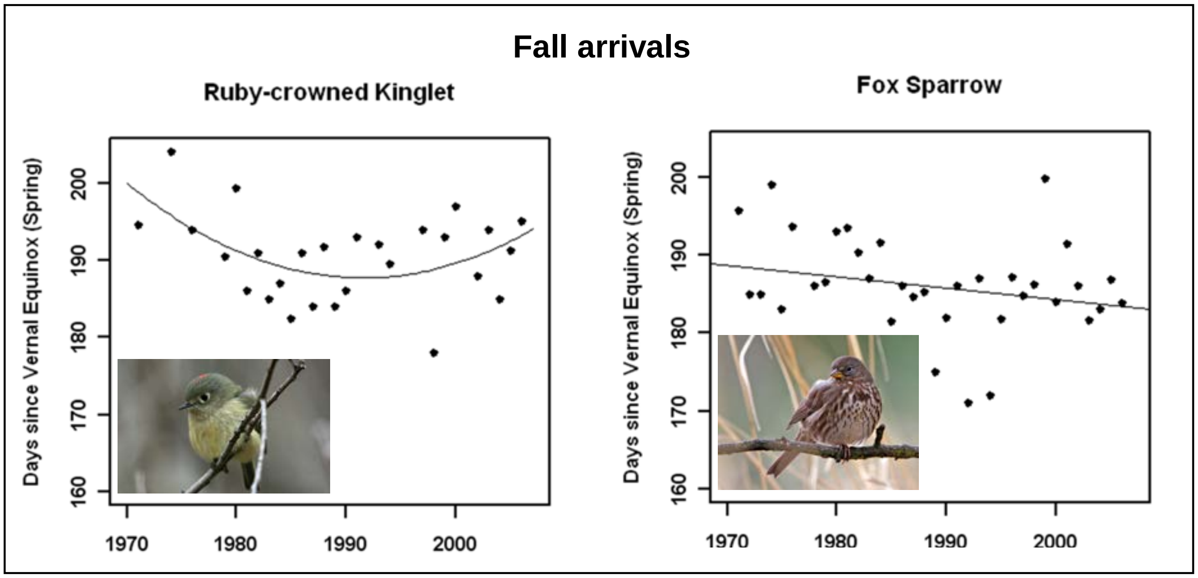
MIGRATORY BIRD ARRIVALS (NO UPDATE)

Spring and fall arrivals of some migratory birds are changing.





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, 2007j; 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; 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, John 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, Root 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). Instead of using Julian or calendar dates, arrival dates were transformed to "days since vernal equinox" (Sagarin, 2001; Miller-Rushing et al. (2008).

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 – 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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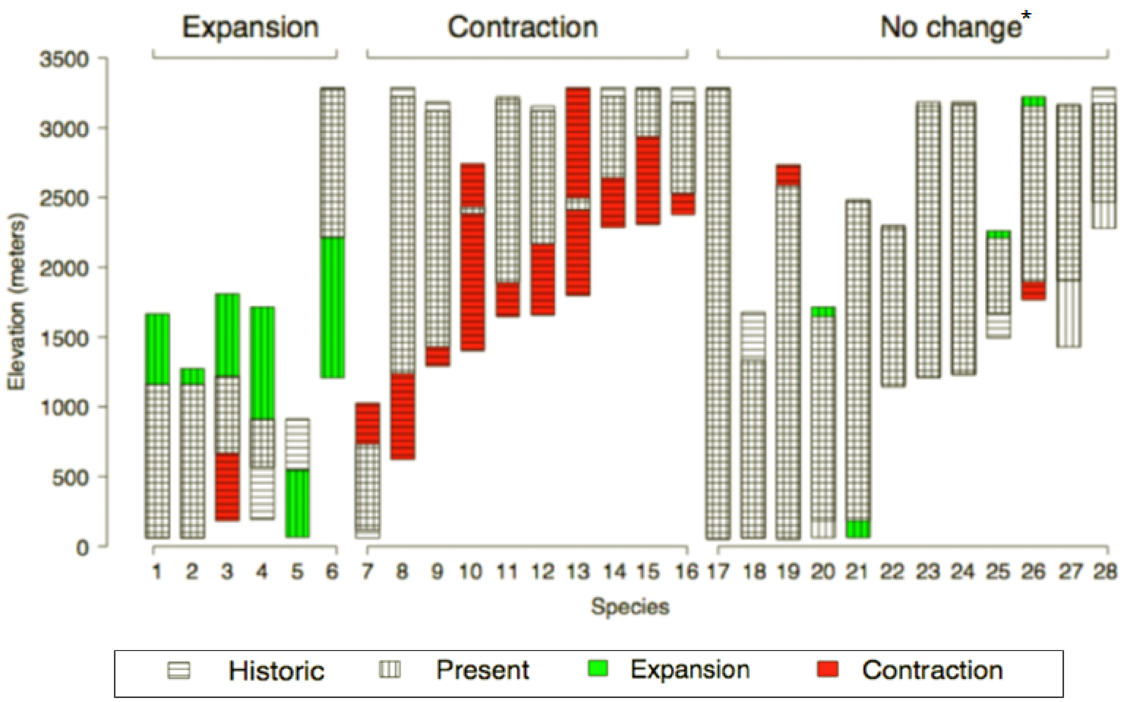
SMALL MAMMAL RANGE SHIFTS (NO UPDATE)

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: C. Moritz, J. L. Patton 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?

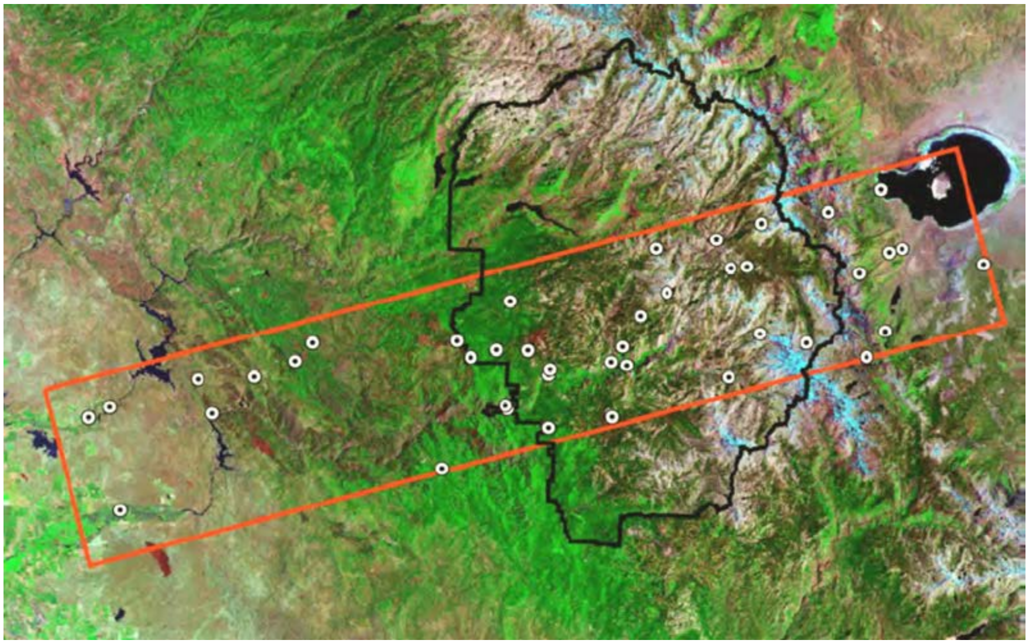
The indicator summarizes changes in the elevational range of small mammals across Yosemite National Park and adjacent areas. It presents a comparison between (a) the historical elevation ranges where species were detected during a survey conducted between 1911 and 1920, and (b) present-day ranges based 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 below). 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

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: C. Moritz, 2007

changes in fauna 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, 2007j). 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).

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 et al., 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 $3^{o}C$, 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 (Tingley and 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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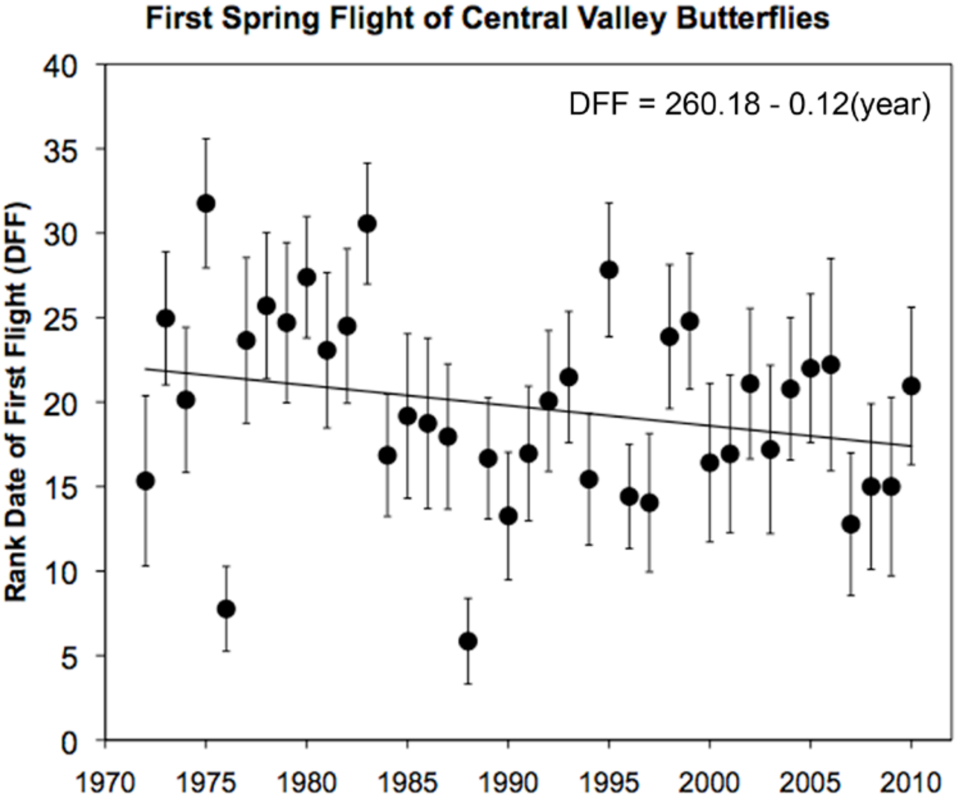
SPRING FLIGHT OF CALIFORNIA CENTRAL VALLEY BUTTERFLIES (UPDATED)

Over the past 39 years, common butterfly species have been appearing in the Central Valley earlier in the spring.

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



Source: Forister and Shapiro 2003
(data updated)

DFF – date of first flight;
Rank Date of First Flight – the average of 23 ranks (corresponding to the 23 species studied) for each year
Error bars represent 95% confidence intervals (see text for explanation)

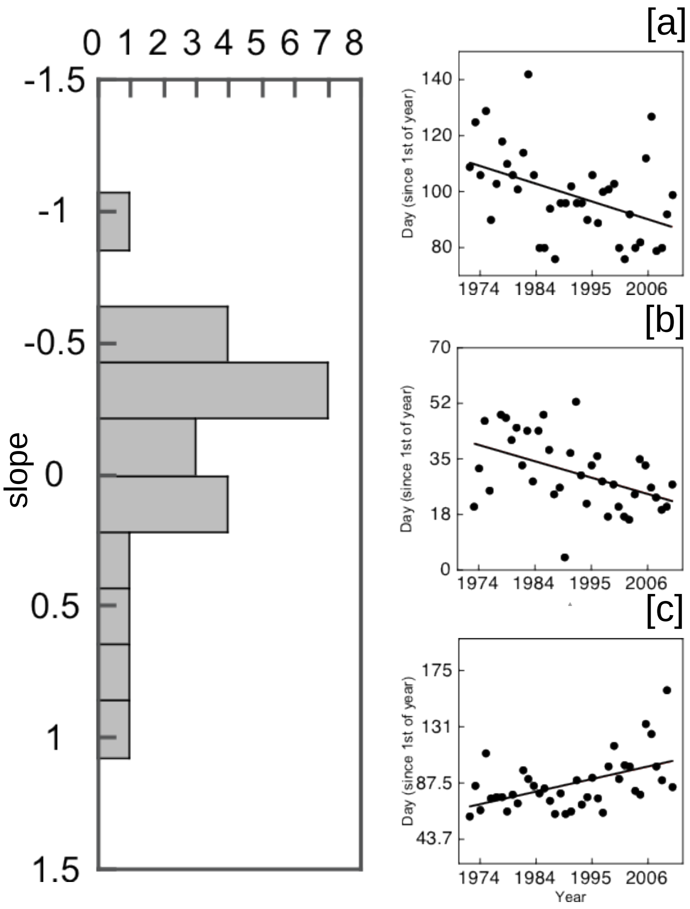
What is the indicator showing?

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 past 39 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 mean "rank date of first flight," derived as follows. For each species, the years were ranked from 1 to 39 (the number of years for which observations are available) based on DFF; the year with the earliest DFF receives the rank of one. The rank DFF shown in the graph is the average of 23 species-specific ranks for each year.

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 studied (errors bars shown on the graph represent 95% confidence intervals).

Beyond the general pattern illustrated in the first graph, differences in species-specific responses require further note. A trend towards earlier emergence was observed for 15 of the 23 species; a trend towards later emergence was observed for 8 species. (See appendix to this indicator for the results of regression analyses [DFFs were regressed against years] for each species.)

Species-specific trends in emergence date



Source: Forister and Shapiro, 2003

The frequency distribution of the slopes relating DFFs to years is shown in the histogram on the right. Negative values towards the top of the histogram correspond to species emerging earlier. Graphs [a] to [c] illustrate DFFs for three of the butterfly species: *A. campestris* [a] and *P. rapae* [b] have been emerging earlier , while *P. catullus* [c] has been emerging later. In addition to being one of the species showing the most dramatic response in DFF, *A. campestris* has expanded the northern limit of its range in the western United States (Crozier, 2002). This expansion has been linked to warmer temperatures.

Issues with interpretation of species-specific patterns, particularly later emergence, are discussed below under “Strengths and Limitations of the Data.”

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 a change in 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, 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 (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 higher-latitude climates. This indicator complements similar studies from Europe and demonstrates the apparently ubiquitous phenological response of spring butterflies to warming and drying conditions (e.g., Roy and Sparks, 2000; Peñuelas et al., 2002). It is also worth noting that the Central Valley has 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 emigrate 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 (Forister and Shapiro, 2003).

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. 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.

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). Eight 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 study area is located in the Central Valley portions (below 65 meter 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 was included as well.

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 DFF is only one aspect of a potentially multi-faceted suite of population-level dynamics. 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? The picture becomes even more complex considering general declines in low-elevation butterfly populations in the region that have been reported by Forister et al. (2010). If populations are in overall decline, with lower densities of individuals throughout the year, this could lower detection probabilities. This is true particularly early in the season for multivoltine species (i.e., species that produce more than one generation in a season, where the first generation tends to be smaller). Lower detection probabilities could appear as later phenological emergence (i.e., a “backwards” shift in time as is shown for *P. catullus* in the bottom right of the second figure). These issues are addressed in more detail in Forister et al. (2011); and for further discussion of relevant biological complexities, see Shapiro et al. (2003) and Thorne et al. (2006).

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APPENDIX: Regression analysis: Date of first flight (DFF) against years

Results of regression analyses (DFFs against years) for each butterfly species. Species are listed in order from the most positive slope to the most negative.

Butterfly species	Slope	R^2	P value
Pholisora catullus	0.92	0.25	0.0011
Lycaena helloides	0.79	0.095	0.057
Phyciodes campestris	0.53	0.030	0.34
Danaus plexippus	0.27	0.022	0.37
Everes comyntas	0.056	0.0029	0.75
Euchloe ausonides	0.054	0.0025	0.78
Nymphalis antiopa	0.035	0.00086	0.86
Erynnis tristis	0.016	0.00	0.96
Pyrgus scriptura	-0.0024	0.00	0.99
Papilio zelicaon	-0.034	0.0014	0.82
Vanessa annabella	-0.13	0.0073	0.61
Polites sabuleti	-0.26	0.047	0.18
Phyciodes mylitta	-0.29	0.048	0.18
Papilio rutulus	-0.29	0.081	0.080
Plebjus acmon	-0.32	0.023	0.36
Hylephila phyleus	-0.33	0.065	0.12
Strymon melinus	-0.36	0.11	0.040
Vanessa cardui	-0.37	0.033	0.26
Pieris rapae	-0.49	0.22	0.0035
Pyrgus communis	-0.49	0.13	0.023
Colias eurytheme	-0.58	0.076	0.093
Atalopedes campestris	-0.60	0.19	0.0055
Vanessa atalanta	-1.03	0.31	0.0003

EFFECTS OF OCEAN ACIDIFICATION ON MARINE ORGANISMS (NEW)

TYPE III INDICATOR

While not an impact of changes in the climate, the biological consequences of changes in ocean chemistry as a result of increasing emissions of carbon dioxide (CO_2) into the atmosphere deserve attention. Ocean chemistry is changing at an unprecedented rate and magnitude due to anthropogenic carbon dioxide emissions to the atmosphere. When CO_2 is absorbed by seawater, increasing dissolved CO_2 concentrations, chemical reactions occur that reduce sea water pH in a process known as “ocean acidification” (see *Acidification of Coastal Waters* indicator, page 32). Scientific research on the biological effects of acidification is still in its infancy and there is much uncertainty surrounding its ultimate effects on marine ecosystems (NAS, 2010).

Several biological processes are known to be sensitive to the expected changes in seawater chemistry. Acidification of sea water decreases the concentration of carbonate ions in the water, thus reducing the availability of calcium carbonate. This is especially dangerous to corals and other organisms that use calcium carbonate to construct skeletons or protective structures. The panel of photographs on the right shows what happens to a pteropod, a shelled marine snail, exposed to sea water chemistry adjusted to that projected for the year 2100 (0.1-0.3 units drop in pH—a 150 percent increase in acidity). Its shell dissolves after approximately 45 days in this environment (NOAA, 2010). These creatures are a major food source for many species of fish.

In addition, scientists project other potential effects of ocean acidification on marine organisms (NOAA, 2010), such as:

- Changes in ionic form of marine nutrients and potentially harmful substances (e.g., metals)
- Increased photosynthetic rates in carbon-fixing organisms
- Altered reproduction and survival in organisms
- Reduced olfaction (sensory function) in fish

Source: NOAA, 2010; photo credit: National Geographic Images

Surface water pH in the California Current System exhibits considerable spatial and temporal variability. This variability could provide the basis for a certain degree of adaptability by marine organisms in this region to future ocean acidification (Hauri et al., 2009). It is not known how marine organisms will acclimate or adapt to the chemical changes. Based on current knowledge, it seems likely that effects will first be seen in animal groups with finely tuned ranges of environmental conditions (NAS, 2010).

In recent years, considerable research has been initiated to study the physical, chemical and biological aspects of ocean acidification. Of particular note is the National Oceanic and Atmospheric Administration's (NOAA) implementation of a research plan intended to predict how ecosystems will respond to acidification and to provide information that resources managers can use to address acidification issues. The plan involves a multidisciplinary program of field observations, laboratory studies and modeling, conducted in partnership with other federal and state agencies, universities and research institutions (NOAA, 2010). On the West Coast, scientists from the Monterey Bay Aquarium Research Institute are collaborating with Stanford University and NOAA to study acidification impacts along the California and Oregon coast (MBARI, 2011).

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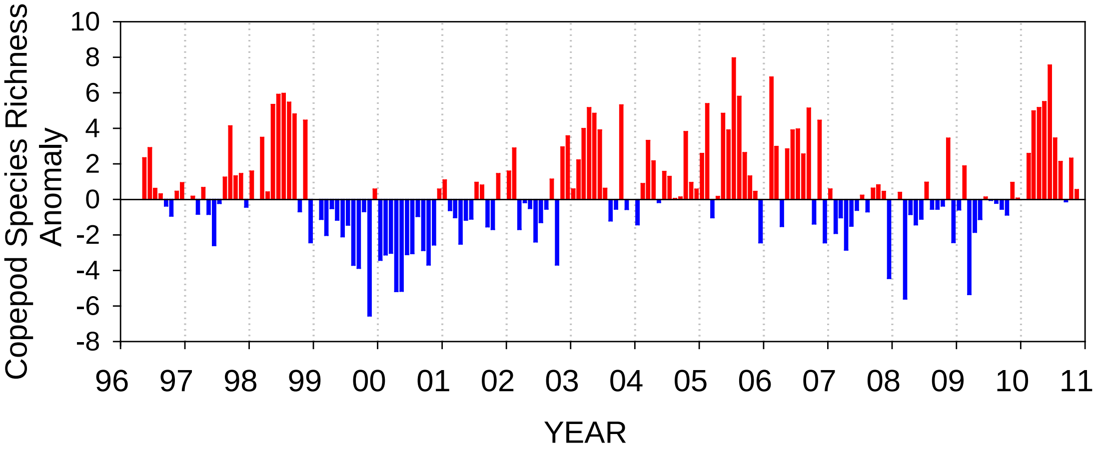
COPEPOD POPULATIONS (UPDATED)

Variations in copepod populations in the Northern California Current ecosystem reflect large-scale and regional 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, 2010

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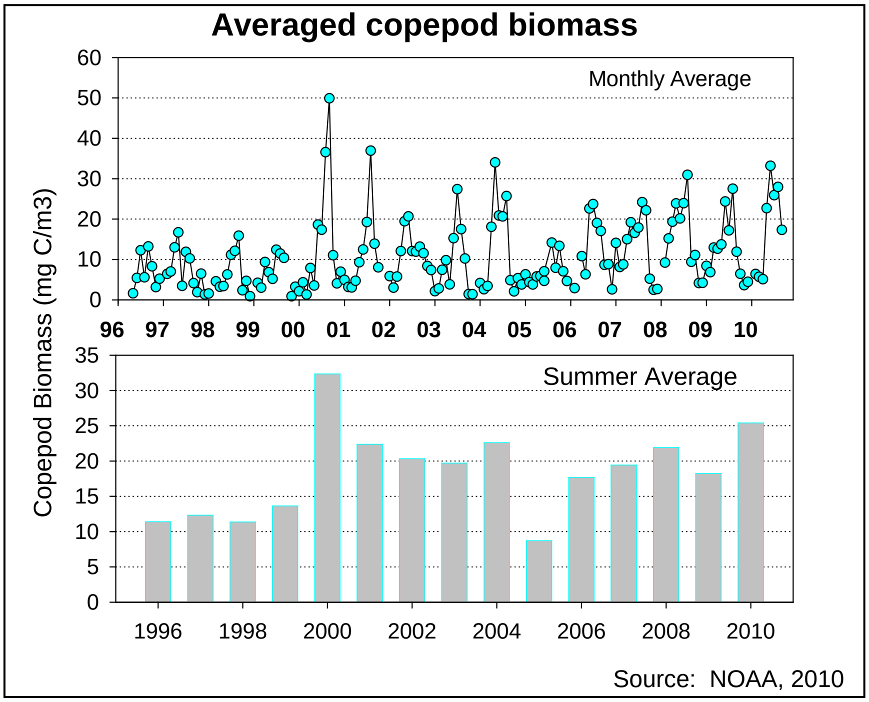
* **Copepod species richness** is the average number of copepod species in a sample of plankton. The anomaly is the difference between the monthly, and the long-term, average copepod species richness values.



Source: NOAA, 2010

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. 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. 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, low from 2007-2009, followed by a jump to very high values during most of 2010. For further details see Peterson (2009).

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. 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. Since that year, biomass has been on the increase with the second highest value of the time series seen in 2010. High copepod biomass is usually 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. 2010 is an exception, for unknown reasons.

While copepod population metrics predominantly describe 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.

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 bioenergetically 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.

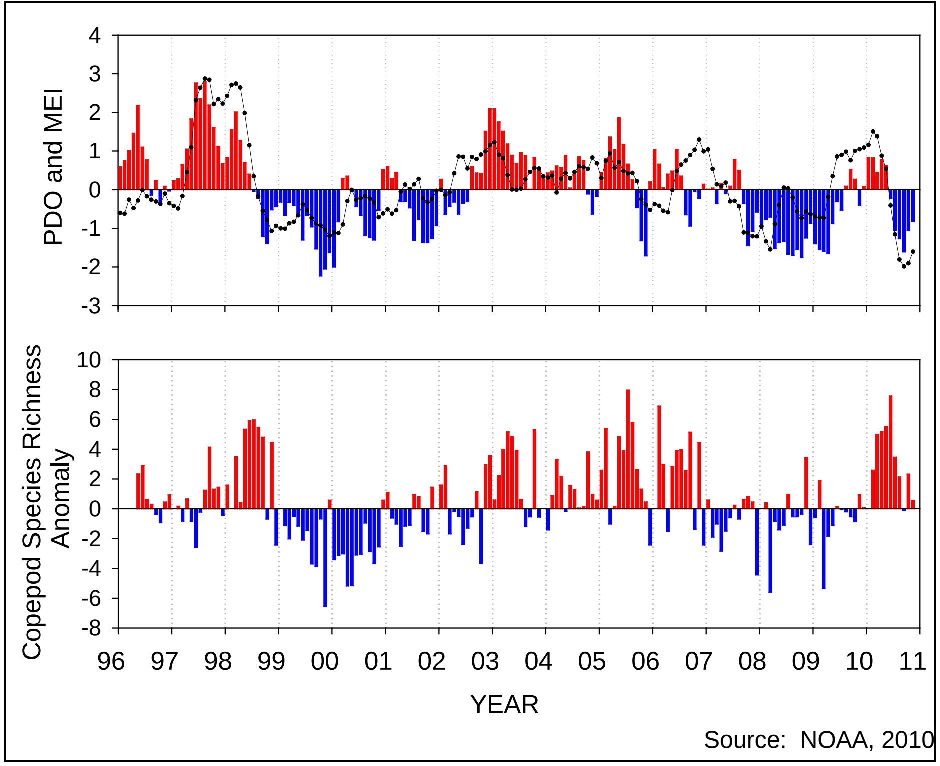
Like other zooplankton, copepods are useful in the study of ecosystem response to climate variability. Due to their short life cycles (on the order of weeks), their populations respond to, and reflect short-term and seasonal changes in environmental conditions. Moreover, many zooplankton taxa are indicator 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, subtropical 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 Coho and Chinook salmon runs along the Washington/Oregon coasts based on certain indices (see http://www.nwfsc.noaa.gov/ and click on “Ocean Conditions and Salmon Forecasting”, in the “Data Products and Tools” box). These same copepod indices have been correlated with: anchovy recruitment (Emmett, personal communication) (recruitment” means the addition of young to a population); sablefish recruitment (Schirippa, personal communication); seabird nesting success in Central California (Sydeman, personal communication); and seabird mortality off northern Washington (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.

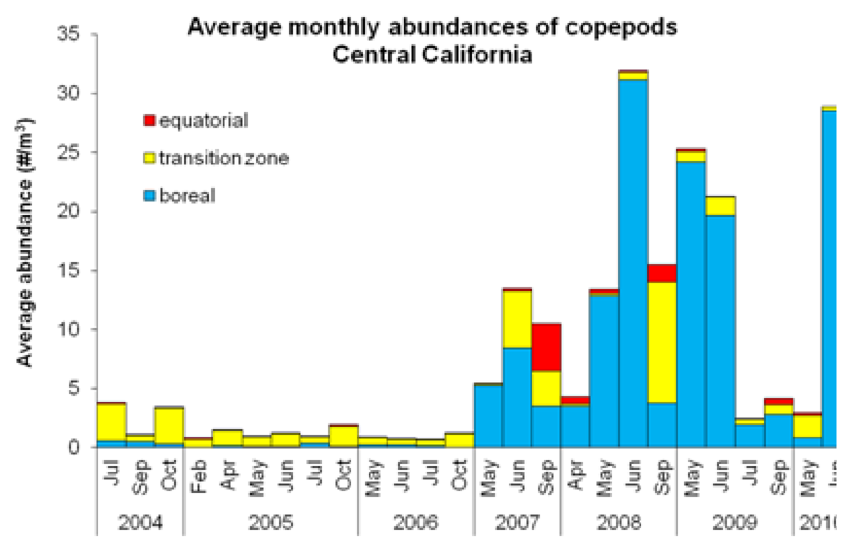
The interannual patterns of species richness are found to track two measures of ocean climate variability: the Pacific Decadal Oscillation (PDO) and the Multivariate El Niño Southern Oscillation Index (MEI). The PDO is a climate index based on ocean temperatures across the entire North Pacific Ocean. 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, 2010

The graph on the right, top panel, shows two time series: monthly values of the PDO (red and blue bars) and the MEI (black dots and lines). The lower panel shows monthly anomalies in the number of copepod species in plankton samples (the same graph is presented on page 191). There are clear relationships between interannual variability in the physical climate indicators (PDO and MEI) and copepod species richness anomalies

Similarly, a 7-year study of copepod populations along the Central California Coast found correlations between copepod composition and ocean current conditions (Elliott et al., 2012). Copepod data was collected from the Applied California Current Ecosystem Studies (ACCESS, http://www.accessoceans.org/) Partnership surveys in the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries. Copepod species were classified into three geographical categories: *boreal* (northern distribution), *transition zone* (mid-latitudes of Central California Current), and *equatorial* (southern distribution).



Source: Elliott et al., 2012

As shown in the figure on the right, all three copepod categories had relatively low abundances in 2004, 2005 and 2006, which were warm-water, poor ocean productivity years (i.e., El Niño conditions). Transition zone and especially boreal copepods showed consistent positive correlations during cold-water productive ocean conditions (i.e., La Niña conditions). The study showed the North Pacific Gyre Oscillation (NPGO) to be the climate variable that best correlates with copepod abundances. The NPGO is an indicator of nutrient and productivity conditions in the California Current. The PDO also correlated well with the copepods, as it has in other regions of the California Current (Peterson and Keister, 2003). While correlations between equatorial and transition zone copepods and the climate variables were mixed, boreal species showed consistent positive correlations during cold-water, strong upwelling ocean conditions. Thus, boreal copepods appear to be good indicators of ocean conditions in the Central California Current.

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 the sampling program and data analysis can be seen in Peterson and Schwing, 2003; Peterson and Keister, 2003; 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 16 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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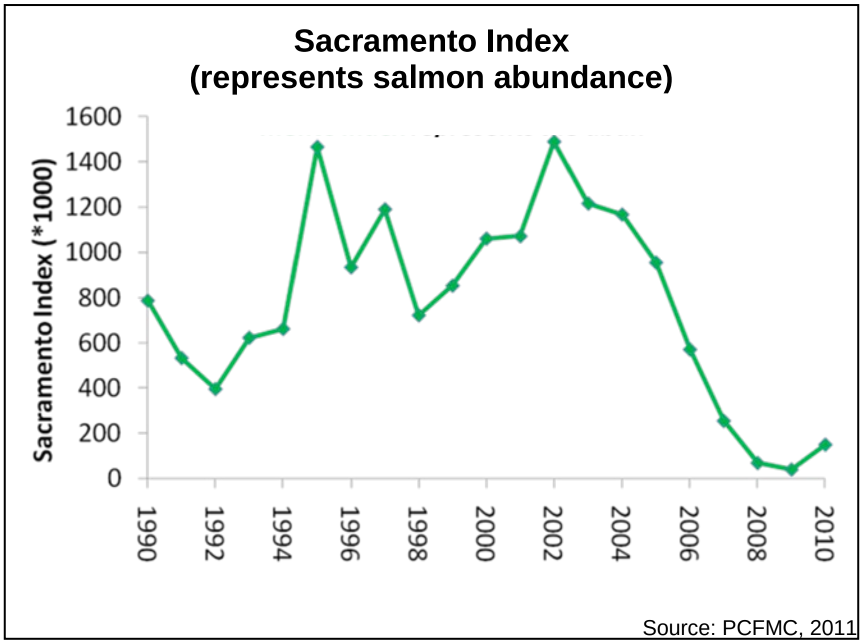
SACRAMENTO FALL RUN CHINOOK SALMON ABUNDANCE (NEW)

Salmon juvenile survival, and resultant adult abundance, has become more variable through time with extreme juvenile mortality events in 2005 and 2006.

Photo: Allen Harthorn

Central Valley chinook salmon (*Oncorhynchus tshawytscha*) rear in the fresh water of the Central Valley, migrate to feeding grounds in the Pacific Ocean, and return to fresh water to spawn. Survival during the initial months of ocean life is dependent on available prey (largely krill, forage fish and crab larvae).



Sacramento Index
(represents salmon abundance)

Source: PCFMC, 2011

What is the indicator showing?

Scientists have found strong evidence that growth and survival of chinook salmon during the first period at sea largely determines later adult abundance. Chinook salmon abundance fluctuates year to year but since 2004 has declined dramatically in the Central California region. The graph shows the abundance of adult fall run chinook salmon originating from the region between 1990 and 2010 (PCFMC, 2011). Abundance is represented by the *Sacramento Index* which is the sum total of adult salmon in the harvest and the spawning grounds (O'Farrell et al., 2008). This index describes the cumulative result of overall conditions in the region that support chinook salmon over the previous two years.

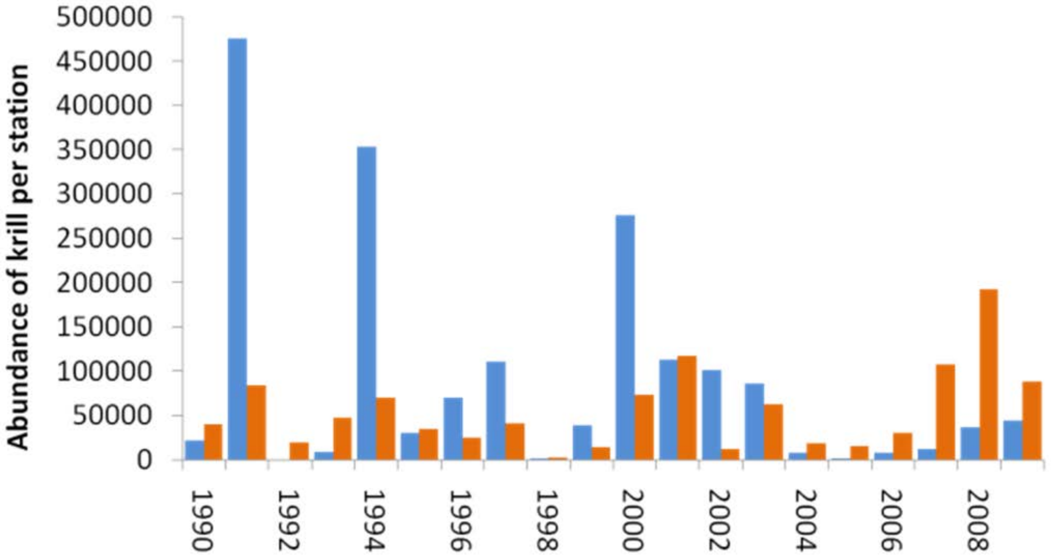
Why is the indicator important?

The chinook salmon is the largest of the Pacific Ocean species and has great cultural, economic and ecological value. These fish are legendary for their migrations from the streams where they are hatched, across vast stretches of the Pacific Ocean, and back to spawn in their streams of origin. Sacramento River fall chinook salmon have been the largest contributor to ocean salmon harvest off California and Oregon for decades (O'Farrell et al., 2008). As a top predator, salmon can inform us of ocean ecosystem health. In combination with an understanding of the processes underlying salmon abundance, scientists can use the conditions of the ocean ecosystem two years prior to allow for rough estimates of the future abundance of adult chinook salmon. Climate change-related influences on the ocean (e.g., increased sea surface temperature and upwelling changes) may enter into predictions of future salmon abundance.

What factors influence this indicator?

The distribution of krill and other prey in the Gulf of the Farallones is related to the abundance of adult salmon two years later. If prey is not in the proximity of the juvenile salmon feeding grounds, adult salmon survival will be lower. Production of krill and other prey in the Gulf is dependent on an appropriate timing and strength of upwelling winds (see Appendix A). Weak or late-onset upwelling, such as during El Niño-like conditions, lead to a warmer layer at the surface of the water column due to limited deep mixing. When this occurs, krill abundance is shifted southward away from where juvenile salmon reside and out of their feeding area.

Krill abundance in the Gulf of the Farallones (blue bars) and in the Central-Northern California region (orange bars)



Source: PCFMC, 2011

The graph above shows krill abundance in the Gulf of the Farallones (blue bars), where juvenile salmon feed as they enter the ocean, between 1990 and 2010 (O'Farrell et al., 2008). Typically the amount of krill in the Gulf is greater than in the other surface waters in the central-northern California region (orange bars). However, in recent years there has been a shift to higher krill abundance in the greater region and less in the Gulf.

The rapid decline in krill in the juvenile salmon feeding area beginning in 2001 and up through 2007 parallels the sharp decline in salmon abundance beginning in 2004. The upwelling began exceptionally late in 2005 and 2006, creating a mismatch between juvenile salmon entering the ocean and available food (Lindley et al., 2009). Because krill became more abundant in the Gulf area in 2009, salmon abundance was predicted to and has rebounded in 2011 from the recent collapse.

Although the salmon-prey relationship and its dependence on ocean dynamics appear to be well-established, it is not yet clear whether increasingly variable ocean processes reflect climate change. The success of salmon populations also depends on conditions in streams and in the Sacramento-San Joaquin Delta, important habitat for early life stages. For example, water flow and temperature conditions necessary for salmon growth and survival are impacted by dams, diversions, land use and bedded sediments. Furthermore, overfishing of salmon both inland and at sea can influence measures of salmon abundance.

Technical Considerations

Data Characteristics

The Sacramento Index is derived from the sum of Sacramento River Fall Chinook (SRFC) ocean fishery harvest south of Cape Falcon between September 1 and August 31; the recreational harvest of SRFC in the Sacramento River Basin; and adult escapement (counts of fish returning to spawn) (O'Farrell et al., 2008). The data were obtained from the Pacific Fisheries Management Council (http://www.pcouncil.org/salmon/stock-assessment-and-fishery-evaluation-safe-documents/preseason-reports/2011-preseason-report-i/).

Strengths and Limitations of the Data

The Sacramento Index has been calculated for a period of three decades. The techniques for estimating the index have been well vetted. However, the index does not account for the different age classes of salmon. Environmental conditions are known to alter the age structure of the population. For example, ocean upwelling and prey availability can enhance or retard salmon maturation, affect their return to spawn, and thus alter the population's age structure. Changes in age structure introduce uncertainty into the relationships between krill availability and fall-run salmon abundance. Wells et al. (2007) demonstrated that poor ocean conditions can lead to a later age at maturation and consequently the age structure of the population could be greater than average during those years. A more rigorous index of abundance would identify age class of the individuals and thereby capture the environmental effects on the population from a specific year.

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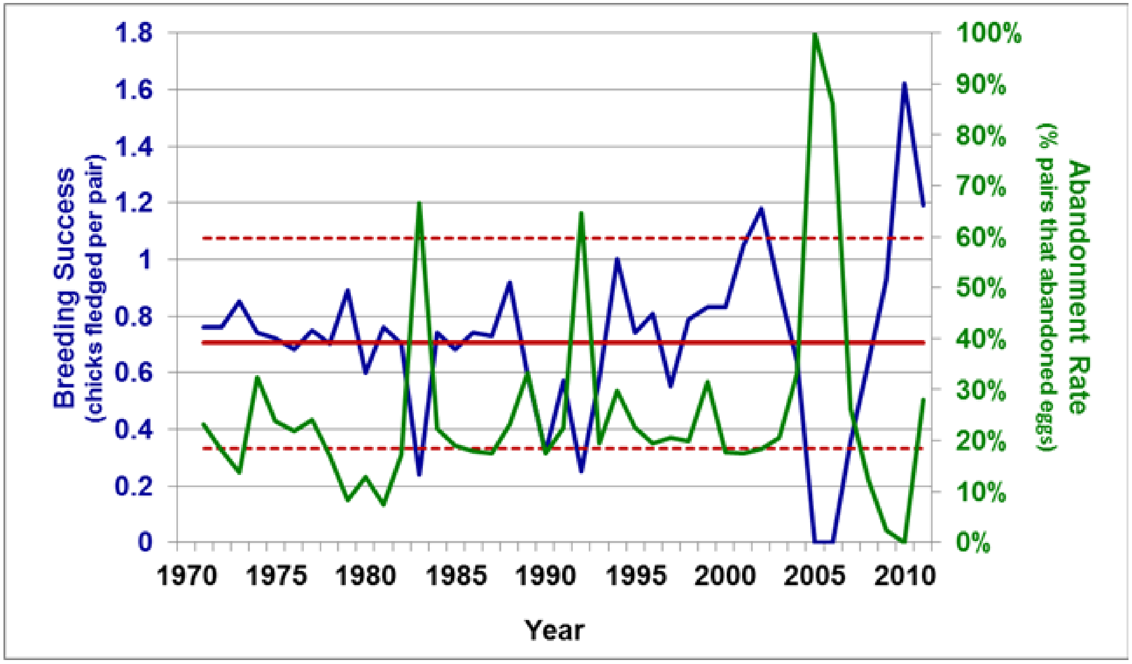
CASSIN'S AUKLET BREEDING SUCCESS* (UPDATED)

Auklet breeding success has become more variable through time, with unprecedented reproductive failures in 2005 and 2006 and record high productivity during 2010.

The Cassin's Auklet (*Ptychoramphus aleuticus*) is a small, diving seabird. Its breeding range extends from the Aleutian Islands, Alaska to islands off the 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) and on the Channel Islands off southern California. These birds eat zooplankton, primarily calanoid copepods off British Columbia and euphausiids (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.*

Source: PRBO, 2012

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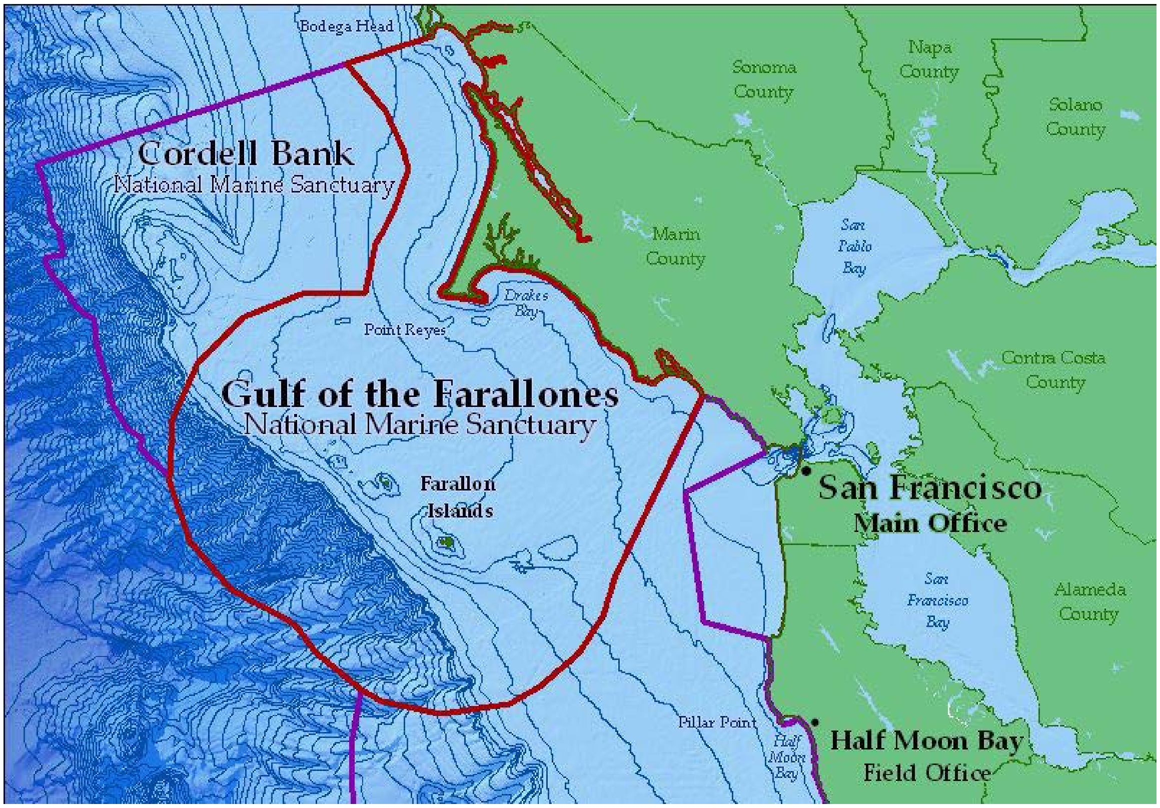
[*] The narrative for this indicator in the 2009 *Indicators of Climate Change in California Report* was authored by Dr. William Sydeman, Farallon Institute for Advanced Ecosystem Research.

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) on Southeast Farallon Island (see map, below). The same data are summarized by decade in the table on the right. 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 two highest and two lowest years on record happening within the past decade (Peterson et al., 2006; Sydeman et al., 2006; PRBO, Unpublished data). Cassin's auklets are the only alcid (i.e., birds belonging to the Alcidae family) which are capable of rearing a second brood after successfully fledging their first chick. Although the rate of successful second broods is generally low, some pairs are able to accomplish the feat, allowing productivity to exceed 1 chick per pair in exceptionally good years. Note that there have only been two years where the mean productivity for the population exceeded this threshold, both within the past decade. Furthermore, although significant drops in breeding success occurred in 1983, 1990, and 1992, complete failure was not observed until 2005, and then repeated in 2006. These extreme highs and lows highlight the increased variability in the ecosystem over the past decade and the auklets' ability to indicate these changes.

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

Decade	Mean Breeding Success	Coefficient of variation
1971-1980	0.745	11.0
1981-1990	0.652	31.2
1991-2010	0.732	75.4



Source: NOAA, 2012

The graph also shows an “abandonment rate,” which is calculated as the proportion of breeding pairs which permanently left eggs unattended during incubation. When oceanographic conditions are unfavorable and prey is scarce, auklets are more likely to abandon the breeding effort and prioritize energy expenditure to maximize adult survival. 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. 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 auklets not only reducing breeding effort, but also emigrating from the Gulf of the Farallones to more productive waters off of southern California. Conversely, in “average” or productive years, abandonment rates are below 30% and in exceptionally good years close to zero. During 2010 for example, though a small number of eggs failed to hatch, there were no birds that abandoned. This suggests a local prey source abundant enough to both sustain adult survival and support high chick production.

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 (Lee et al., 2007; Wolf et al., 2009). 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 (Ainley et al., 1995; 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). `

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 may reduce the efficacy of upwelling—the upward movement of deep, cold, nutrient-rich waters to the surface, where plankton growth occurs (Levitus et al., 2001; Snyder et al., 2003). 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). This trend continues to this day, despite high zooplankton abundance in a few years. 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.

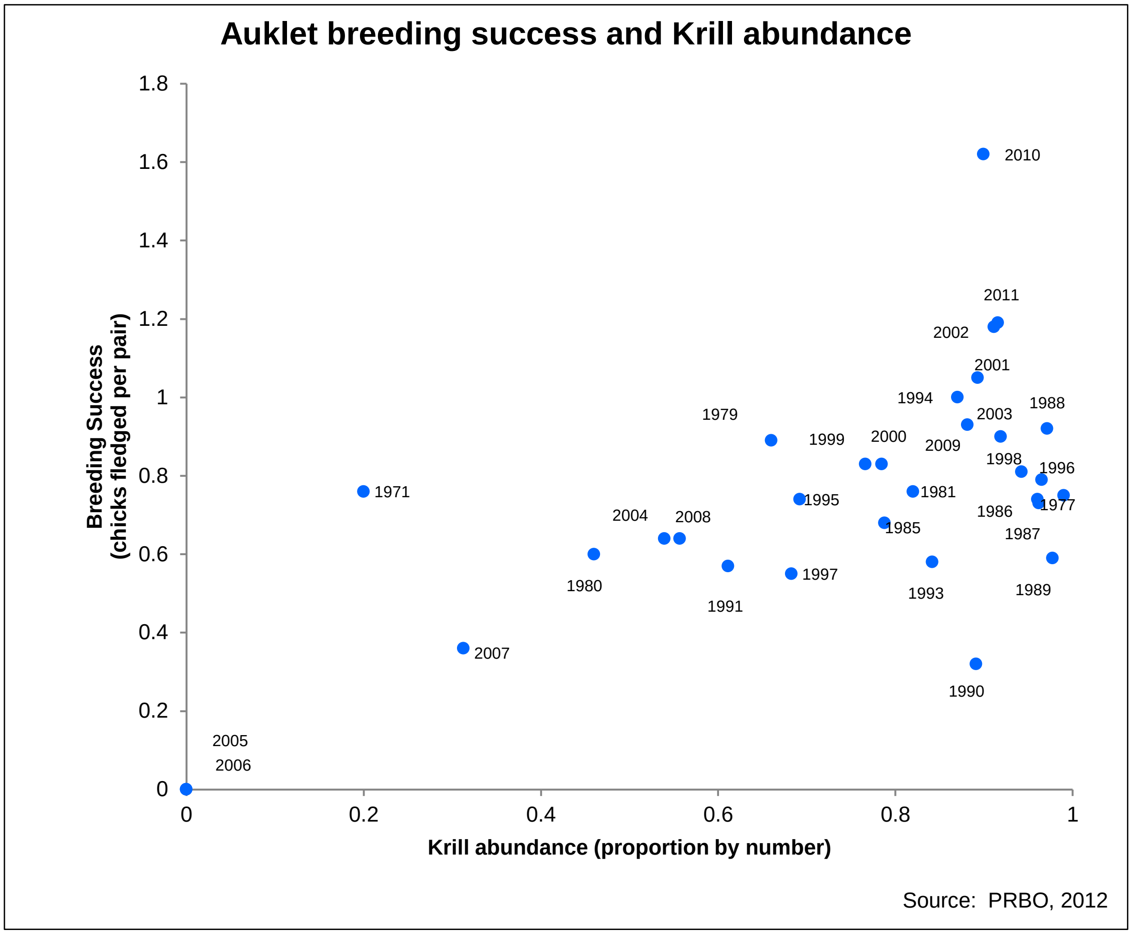
What factors influence this indicator?

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 in order to time hatching so chicks have a reliable food source (Abraham and Sydeman, 2004). However, 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. Although 2005 and 2006 were not characterized as El Niño, the results were similar. Zooplankton abundance in the region was reduced and auklets were not able to adapt, instead choosing to abandon the breeding effort entirely (Sydeman et al., 2006; Jahncke et al., 2008).

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 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). 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). Conversely, in years when krill was abundant in the region (i.e. 2001, 2002, 2010), auklets exhibited high productivity and low abandonment rates.

Auklet breeding success is positively related to krill abundance as shown in the graph on the next page. This figure estimates the abundance of krill as the proportion by number in diet samples, for both species known to be consumed by auklets, and collected at the Farallones. Those years with the lowest breeding success also showed a marked absence of krill in the diet, likely reflecting changes in the distribution or actual abundance of krill within the auklet's foraging range. Likewise, krill was a major component of the diet in years of high auklet breeding success. Trawl data supports the trends observed in the auklet diet. Biomass estimates were higher in years when auklet diet had a higher proportion of krill (Abraham and Sydeman, 2004; Sydeman et al., 2006).



Source: PRBO, 2012

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). Greater than 90 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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SHEARWATER AND AUKLET POPULATIONS OFF SOUTHERN CALIFORNIA (NEW)

Sooty Shearwater and Cassin's Auklet populations at sea in the Southern California Bight have declined significantly over the past 24 years.

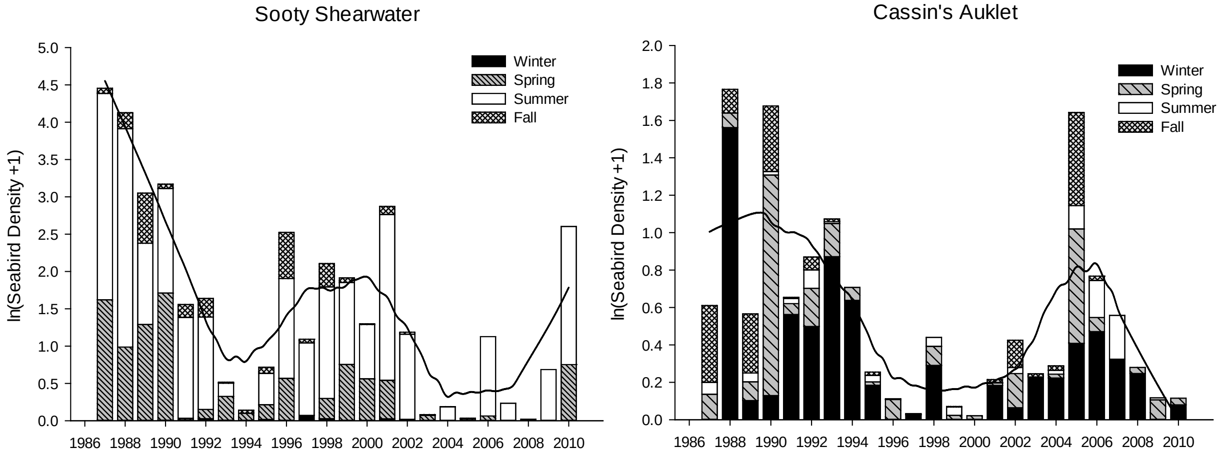
The Sooty Shearwater (*Puffinus griseus*) and Cassin's Auklet (*Ptychoramphus aleuticus*) are abundant seabirds of the North Pacific Ocean. The shearwater is a trans-hemispheric migrant species (Shaffer et al., 2006), whereas the auklet is a local breeder (Abraham and Sydeman, 2004). Shearwaters may be found off southern California year-round, with numbers generally increasing each spring. While in the California Current, shearwaters forage on a variety of nektonic prey including euphausiids, market squid (*Loligo opalescens*), and forage fish (Briggs and Chu, 1987). Auklets are present year-round and forage mainly on euphausiids and larval fish (Ainley et al., 1996).

Sooty Shearwater

Cassin's auklet

Euphasiid (Krill)

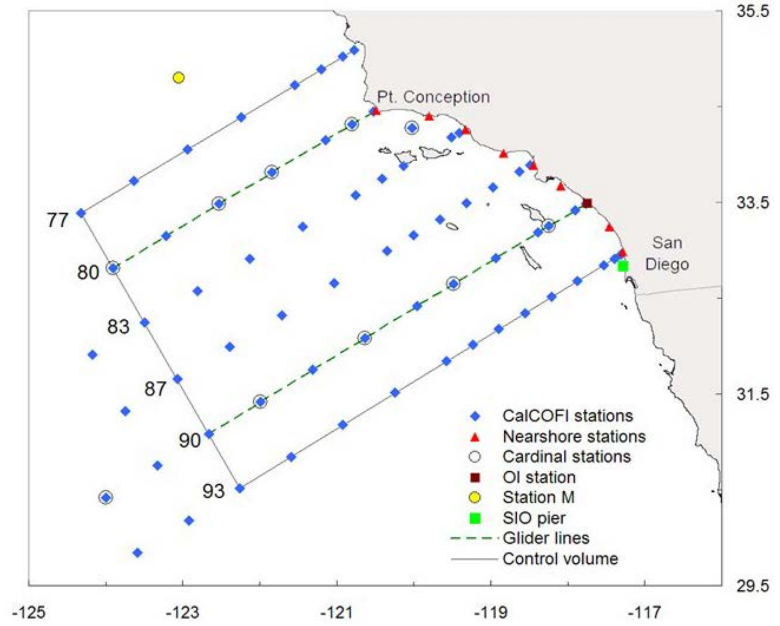
Changes in relative abundance (birds km^{-2})
on 84 CalCOFI surveys, May 1987 - July 2010



Stacked bars denote seasonal density estimates, with a Lowess smoothing line (bandwidth=0.3) shown for each species based on the summed annual value. Note: Shearwater data for fall ended in 2006.

What is the indicator showing?

Surveys of marine birds provide the data for this indicator. (A map of the survey area is on the following page.) Shearwaters were found to be most abundant during the summer (July-August), with lower relative abundance in fall (September-October-



Survey area

Source: CalCOFI

November) and spring (March-April-May). These surveys were carried out in conjunction with seasonal cruises conducted by California Cooperative Oceanic Fisheries Investigations (CalCOFI)/California Current Long Term Ecological Research (CCE-LTER) since May 1987 (Veit et al., 1996). Over the 24 years of the survey, the density of shearwaters declined in each season, including seasons of relatively low abundance (winter, spring, fall). The decline was notably most significant during fall, though data for that season ended in 2006. During the spring-summer-fall, the rate of decline in shearwater density was -4.2% per year over the 24-year period, reflecting an overall decline of over 90%. Average annual density was greatest during 1987-1988 (all seasons combined: 5.51 birds/km^2) and lowest in 2003-2008 (0.04 birds/km^2). Numbers increased in 2009-2010 (1.49 birds/km^2). Interannual variability was considerable, with peaks in 1987-1988, 2001, and 2010; however, each successive peak in abundance was lower than the previous.

In contrast, auklets were most abundant during the winter surveys (January-February). In winter and spring, auklet density declined, but increased in summer; the fall trend was insignificant (P>0.1). During winter, the rate of decline in auklet density was -2.6% per year over the study period. Mean annual density was greatest during 1988 (all seasons combined: 0.99 birds/km^2), 1990 (0.71 birds/km^2), 1993 (0.40 birds/km^2), and 2005 (0.53 birds/km^2), and lowest in 1995-2000 (0.04 birds/km^2). Opposite the pattern shown for shearwaters, numbers decreased in 2009-2010 (0.05 birds/km^2).

See the appendix to this indicator for seasonal summary data for both birds.

Why is this indicator important?

Seabirds, as the most conspicuous marine organisms living at the interface of the atmosphere and the ocean, provide useful information on the spatial and temporal variability of marine ecosystem productivity and 'health'. As top marine predators, shearwaters and auklets respond to changes in ecosystem productivity, which are hypothesized to decrease due to climate change. Hence, tracking the populations of these birds tests the hypothesis that decreases in ecosystem productivity due to ocean warming lead to declines in bird populations (McGowan et al., 1998; Hyrenbach and

Veit, 2003). Consequently, the shearwater and auklet indicators are important because they reflect complex biological processes occurring in the marine environment that are difficult to measure directly.

What factors influence this indicator?

Patterns of population variability in shearwaters and auklets at sea off southern California support the hypothesis that climate change is affecting the marine ecosystem. The surveys found secular change in the populations (density as a proxy of abundance) of both species. The change in shearwaters was most pronounced in spring and fall when the shearwater was less abundant than in the summer. This timing corresponds to periods of substantial migratory movements in and out of the system in spring and fall, respectively. Trends in auklets were most pronounced in winter, corresponding to their seasonal peak of abundance.

These findings support previous analyses of these data sets (Veit et al., 1996; Veit et al., 1997; Hyrenbach and Veit, 2003), and show that the previously described declines in these species have continued through 2010. As shearwaters and auklets are both species with cold-water affinities (Hyrenbach and Veit, 2003) and have spatial associations with euphausiids (Santora et al., 2011), changes in these populations may be related to ocean warming and changes in the distribution, abundance or spatial organization of krill. Shearwaters consume other nektonic prey including forage fish, so variability in other prey populations is another possible explanation for changes in shearwater abundance.

In addition to the observed secular trends in abundance, interannual variability and some strongly contrasting patterns of variability between the species are also evident. For example, over the period 1995-2000, the abundance of shearwaters was relatively stable at moderate levels while auklets were observed at very low abundance; from 2003-2008, a substantial decline in shearwaters occurred, while auklet abundance increased. Thus, there are some similarities (both species have declined), but also some major differences in the population variability of these species. This variation may be related to the fact that shearwaters are wintering migrants while the auklets are local breeders. The relative abundance of shearwaters may be a function of ecosystem productivity and prey availability alone, whereas the abundance of auklets may be a function of prey and other intrinsic population factors such as breeding effort. From 2005 through 2007, auklet reproductive effort on their major breeding site, SE Farallon Island, was compromised by poor prey availability in the Gulf of the Farallones (Sydeman et al., 2006; Sydeman et al., 2009). Auklets abandoned the SE Farallon Island colony (~400 km of the north of the study area) in large numbers in both years in May (see *Cassin's Auklet Breeding Success* indicator, page 202). After abandonment birds may have moved to the Southern California Bight (SCB) in search of prey, resulting in apparent population increases in these years. In 2009 and 2010, prey, in particular krill resources in the Gulf of the Farallones, improved dramatically (NMFS, unpublished data) and the auklets demonstrated significantly above average reproductive effort and success. As a result, population numbers in the SCB declined as birds re-distributed northwards for reproduction.

The complexity in breeding effort of auklets and other factors for both auklets and shearwaters make it challenging to attribute the population changes just to climate change and climate variability. While some investigators (Veit et al., 1996; Veit et al., 1997) concluded that shearwaters declined in the CalCOFI region due to ocean warming and changes in their prey base, others (Spear and Ainley, 1999) countered that the apparent shearwater decline in the California Current was actually a redistribution of the birds to oceanic domains to the west of the SCB rather than a real population decline. Population declines, however, at very large breeding colonies of shearwaters in New Zealand Scott, Scofield et al., 2008 support the claim of population decline (made by Veit et al. (1997)). Additionally, even if the population change was simply due to re-distribution (as is no doubt the case for auklets), the question remains: why did re-distribution occur? Furthermore, population declines of the shearwater are likely as hundreds of thousands were killed in drift gill nets in the western North Pacific during the 1980s and early 1990s. Population declines of auklets on the Farallones have been well-documented (Lee et al., 2007). Therefore, the investigators are confident that the declining trends in these species in this analysis are real, as supported by studies at breeding colonies. However, in addition to climatic factors, anthropogenic and natural factors may have played a role. Finally, attribution to climate change requires examining physical changes in the environment resulting from human-induced warming as well as making direct linkages of these physical changes to responses observed in seabird populations. This would be a difficult and complex undertaking and is well beyond the scope of this report, but clearly points to future research needs for this long-term dataset.

Technical Considerations

Data Characteristics

Surveys of marine birds have been conducted in conjunction with seasonal California Cooperative Oceanic Fisheries Investigation (CalCOFI) and California Current Ecosystem-Long-Term Ecological Research (CCE-LTER) cruises since May 1987 (Veit et al., 1996). The resulting database now contains 84 surveys over 24 years, including information through July 2010. Observational methods in brief are as follows: While the ship is underway at speeds >5 knots, seabirds are identified and counted by an experienced observer using a 300-m strip-width transect (see Yen et al. (2006) for details). Survey data were used to illustrate patterns of variability in the relative abundance of two species, the Sooty Shearwater (*Puffinus griseus*) and Cassin's Auklet (*Ptychoramphus aleuticus*), expressed as density of birds at sea (birds/km^2). To test for trends in density though time the investigators used negative binomial regression (for count data), including the areal coverage during each survey (per km^2) as a confounding covariate, and year, to assess temporal trends in each model.

Strengths and Limitations of the Data

Long records of seabird populations at sea are very uncommon. The records of shearwater and auklet density in the Southern California Bight was collected and maintained by Farallon Institute (2007-2011), PRBO Conservation Science (2000-2006), and Scripps Institution of Oceanography (1987-1999). 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.

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Acknowledgements:

Funding for the project that served as the basis for this indicator and write-up is provided by the National Science Foundation (CCE-LTER) and NOAA-Integrated Ocean Observing System via the Southern California Coastal Ocean Observing System (SCCOOS). We thank Richard R. Veit and John McGowan for the vision to initiate the project in the 1980s and Veit and K. David Hyrenbach for sustaining it through the 1990s.

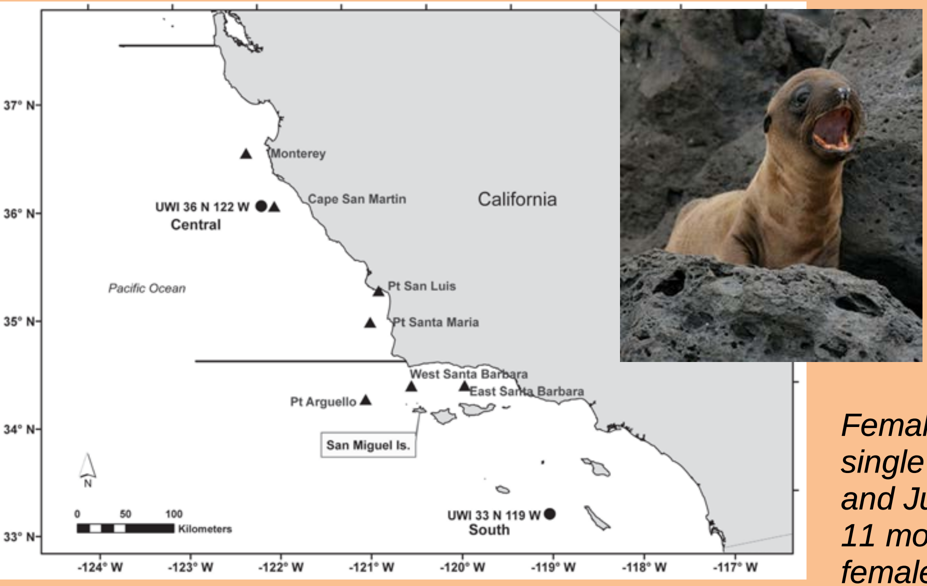
APPENDIX: Seasonal Density Estimates

Seasonal density estimates of Sooty Shearwater and Cassin's Auklet on CalCOFI cruises from May 1987- July 2010. Mean seasonal log (ln)-transformed densities, and results of negative binomial regression on temporal trends (z score and P values) are shown.

	Sooty Shearwater	**Cassin's Auklet**
Winter (Jan.-Feb.)		
Mean	0.113	0.587
Std. Deviation	0.019	0.871
N	18	18
Z (year)	-1.74	-2.67
P>|z|	0.081	0.008
Spring (Mar.-May)		
Mean	0.810	0.206
Std. Deviation	1.274	0.477
N	23	23
Z (year)	-2.7	-1.71
P>|z|	0.007	0.086
Summer (Jun.-Aug.)		
Mean	2.670	0.048
Std. Deviation	3.874	0.072
N	22	22
Z (year)	-1.78	1.01
P>|z|	0.075	0.311
Fall (Sep.-Nov.)		
Mean	0.872	0.132
Std. Deviation	3.217	0.189
N	21	21
Z (year)	-3.57	-0.94
P>|z|	0.000	0.331

SEA LION PUP MORTALITY AND COASTAL STRANDINGS (NEW)

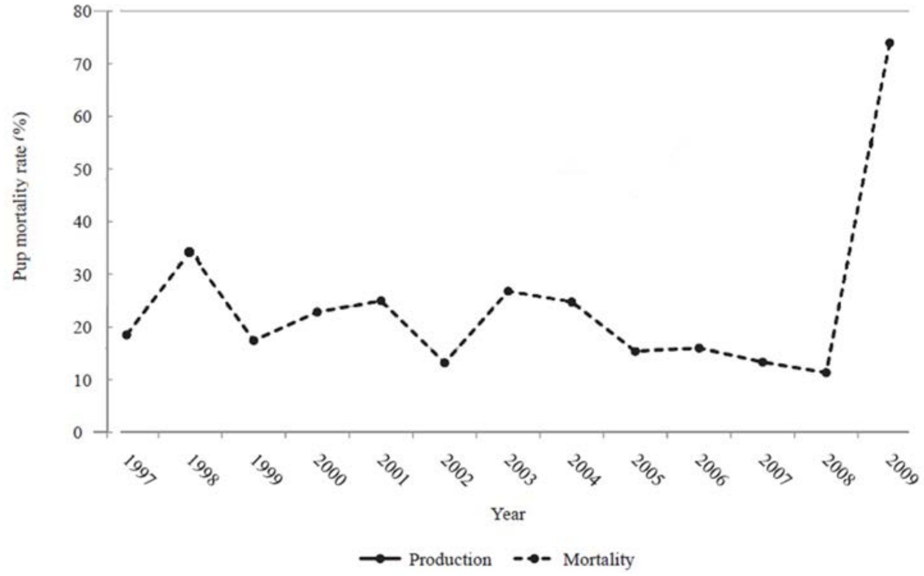
Anomalous oceanographic conditions—mediated through warmer sea surface temperatures—resulted in increased pup mortality among California sea lions and a record number of yearling pup strandings.



Source: Melin et al., 2010
Sea lion photo from http://www.takepart.com/news/tag/sea-lions-climate-change

The California sea lion (Zalophus californianus) is a permanent resident of the California Current System. Its primary breeding colonies are the California Channel Islands. Females give birth to a single pup between May and June. For about 11 months, lactating females travel to sea for 2-5 days to feed and return to nurse their pup.

Sea Lion Pup Mortality Rate
(Point Bennett Study Area, San Miguel Island, California)



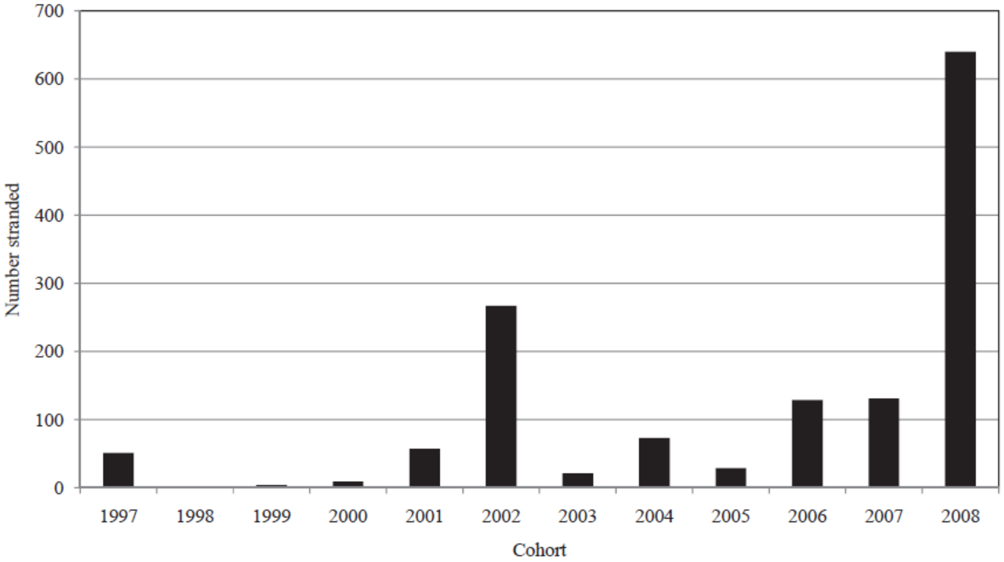
Source: Melin et al., 2010

* Pup mortality rate at 5 weeks of age of California sea lions in the Point Bennett Study area on San Miguel Island, California.

What is the indicator showing?

California sea lion population indices (e.g., pup production, pup mortality and stranding of pups) and oceanic conditions were studied between 1997 and 2009 at San Miguel Island (see map above). The first graph shows that in 2009, early pup mortality (during the first 5 weeks of life) among sea lions was exceptionally high, almost four times greater than the long-term average (74 percent in 2009, compared to 18.7 percent). Pup mortality is based on data from San Miguel Island's Point Bennett Study Area, a large sea lion breeding area used as a long-term index colony for monitoring pup production and mortality (Melin et al, 2010). The high pup mortality rates in 1998 and especially 2009 were associated with anomalously high sea surface temperatures (SST).

Sea lion strandings along the central California Coast*



* *The annual number of weaned California sea lion pups by cohort that stranded due to emaciation between San Luis Obispo and Mendocino counties along the central California coast and that were evaluated by The Marine Mammal Center (Sausalito, CA)*

Source: Melin et al., 2010

The second graph shows the annual number of weaned sea lion pups that were stranded due to emaciation along the central California coast. The bars on the graph represent the number of sea lion pups in a cohort—i.e., the year the pups were born--that were found stranded due to emaciation and transported to the Marine Mammal Center for rehabilitation. Stranding of yearling pups in the 2008 cohort occurred in record numbers in central California in 2009.

Why is this indicator important?

Sea lions and other marine mammals are prominent animals that reflect ecosystem variability and degradation in the ocean environment. Animals at higher levels in the food chain provide insights into relationships among marine community structure and oceanographic conditions (Weise, 2008). Scientists use marine mammals as sentinels of ocean production and changes in food webs, and increasingly include them in studies of changing oceanographic conditions (Moore, 2008).

Sea lions are among the most abundant top predators of the food chain in the offshore California waters. They are vulnerable to the seasonal, annual and multiyear fluctuations in the productivity of the ocean. Sea lion prey such as fish and cephalopods are also influenced by particular sets of environmental conditions along the California coast.

One of the greatest threats to the California sea lion comes from changes in their food resources due to climate and other influences (Learmonth et al., 2006). Air and ocean temperatures are projected to warm, especially in the summer. The biological impacts of these changes may be a lower rate of ocean productivity and thus less food for many species (IPCC, 2007e). Shifts in the abundance and distribution of prey could have serious consequences for sea lion reproduction and survival.

What factors influence this indicator?

Sea lion pup survival is highly dependent on the lactating mother's ability to feed in coastal waters. When prey availability is reduced, lactating females must travel farther to obtain food, and fasting pups are more vulnerable to starvation. Newly weaned pups just learning to forage on their own may also be vulnerable when prey availability is low.

The California Current System (CCS) has a large impact on the food supply and survival of sea lion pups along the coast. 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. This productive zone supports important commercial fisheries as well as marine mammal and sea bird populations. CCS waters are influenced by large-scale, continuing processes associated with the El Niño-Southern Oscillation (ENSO). El Niño conditions associated with the warm phase of ENSO occur irregularly at intervals of two to seven years, often leading to a weakened upwelling, low-nutrient waters and higher sea surface temperatures (SSTs). Increased summertime SSTs due to decreased upwelling strength of ocean currents is reported to reduce availability of prey in the sea lion foraging zone (see Appendix A).

The reduced availability of coastal fish and cephalopods forces sea lions to travel farther to find prey in deeper waters. Lactating females typically travel to sea for two to five days to feed and return to the colony for up to two days to nurse their pup. The pup—solely dependent on its mother until about six months of age—maintains a fasting cycle while the mother is foraging. Hence, lactating females are limited in the distance they can travel and the time away from the colony by the fasting capabilities of their nursing pups. If the duration of the foraging trip exceeds the fasting capacity of the pup, the latter may die of starvation. Further, if the female does not obtain enough prey for her own nutritional and energy needs, she may not be able to support lactation for her pup.

The highest pup mortality rate and record number of strandings in 2009 were associated with anomalous oceanographic conditions along the California coast between May and August. During that year, upwelling was the weakest in the past 40 years; this was accompanied by uncharacteristically warm June SSTs. Negative upwelling patterns and warmer SSTs during the summer required lactating females to take longer than average foraging trips (averaging 7 days, approaching the maximum duration for which pups survive without nursing, 9 days). Additionally, the diet of California sea lions in 2009 varied significantly from other years, with cephalopods and rockfish occurring more frequently. The combination of longer foraging trips and a diet principally of rockfish and cephalopods did not provide adequate energy for lactating females to support their pups.

The record number of stranded year-old pups born in 2008 may also be related to the irregular oceanic conditions in 2009. Most of the strandings occurred in June, the period of the warmest SST and weakest upwelling activities, conditions which likely reduced the availability of sea lion prey to newly weaned pups. Newly weaned sea lions have limited foraging experience and fat stores and, unlike adults, are physiologically unable to travel increased distances and deep depths to obtain prey. The high number of stranded and emaciated weaned pups in 2009 suggests that they were not able to support themselves because of difficulties finding or obtaining food.

Technical considerations

Data characteristics

Population indices (e.g., pup production, pup mortality, stranding of pups) were measured at San Miguel Island, a large sea lion breeding colony. Because of the large size of the colony, index sites were used to estimate population parameters. Pup mortality surveys were conducted in the study area every two weeks between late June and early August and finally the last week of September. Dead pups were removed from the breeding area as they were counted. The total number of observed dead pups for each survey was an estimate of the cumulative mortality of pups at 5 weeks and 3.5 months of age.

Between 1997 and 2009, after all pups were born, observers counted live pups in the study area each year. Mean numbers of live pups were calculated from the total number of live pups counted by each observer. Total pup production was the sum of the mean number of live pups and the cumulative number of dead pups counted up to the time of the live pup survey. Cumulative pup mortality at 5 weeks of age was calculated as the proportion of dead pups of those counted during the live pup survey.

The stranded weaned pups were those transported from along the central coast (San Luis Obispo to Mendocino counties) to The Marine Mammal Center (TMMC) in Sausalito, California between 1997 and 2009. Because standings that occurred in remote areas were not reported and animals that died prior to collection were not counted, the data captured the minimum number of pups that stranded in any year. The dataset was restricted to pups that TMMC veterinarians determined to have stranded due to starvation. Pups were classified as animals that were between 0- and 1-year-old with a birth date of June 15.

Sea surface temperature anomalies were calculated from seven buoys along the central coast. This length of coastline represents the foraging range of the juvenile and lactating female sea lions. The buoy data were obtained from the NOAA National Data Buoy Center (http://ndbc.noaa.gov/rmd.shtml). The mean daily SSTs from the seven buoys were used to calculate mean monthly SSTs and averaged to create monthly sea surface temperature anomaly indices for the years 1997 to 2008.

Strengths and Limitations of the data

Pup mortality:

The study area represents about 45% of the U.S. sea lion breeding population (Melin et al., 2010), thus providing a representative measure of trends in population responses to changes in the ocean environment. Because the area is large, index sites across the colony were used to measure population parameters. Instead of using total counts for pup production and mortality, mean values were used to estimate these parameters.

Strandings:

The stranding dataset was restricted to pups recovered by TMMC because they are responsible for strandings that occur over the largest area of the central coast and have had consistent recovery effort from 1997 to 2009.

Temperature readings:

Sea surface temperature readings were averaged from seven buoys ranging from Monterey down to the San Miguel Island area.

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EMERGING CLIMATE CHANGE ISSUES

Scientists are reporting possible climate-related changes and impacts that are plausibly—but not yet established to be—influenced by climate change. Scientifically defensible hypotheses, models and/or limited data suggest that certain observed or anticipated changes are due to climate change. However, deciphering the influence of climate among other factors both external (such as land use and environmental pollution) and internal (due to inherent, natural variability) to the climate system presents a challenge. Changes in systems that are known to be affected by climatological factors, but where the influence of climate change remains uncertain are discussed in this section as ***emerging issues***.

In this section, a few examples of environmental changes that are plausibly, but not yet established to be, influenced by climate change are discussed. Investigators have hypothesized that climate change is a factor in the occurrence or intensification of these changes. However, additional data or further analysis are needed to determine the extent by which climate change—as opposed to other factors, including inherent variability in the climate system—plays a role. These emerging issues may in the future be tracked as indicators of climate change once sufficient data on the influence of climate change become available. These emerging issues are listed below.

HARMFUL ALGAL BLOOMS

Steve Haddock, MBARI

Worldwide, there has been a trend towards increasing frequency, severity and duration of harmful algal breakouts in all aquatic environments (Moore et al., 2008). Marine outbreaks are commonly called red tides, but scientists prefer to refer to them as harmful algal blooms (HABs). Some harmful algal species produce toxins that can poison fish, birds and marine mammals. Climate change has the potential to affect the occurrence and severity of HABs because the growth, toxicity, and geographic distributions of algae are impacted by variable ocean conditions (NCCOS, 2012). Such conditions include warmer sea surface temperature, increases in carbon dioxide in seawater and ocean acidity, and alteration of marine wind and water circulation patterns (e.g., upwelling systems).

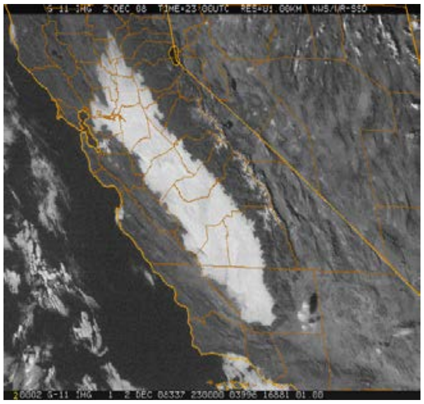
Early monitoring for harmful algal blooms in California was initiated in response to public health concerns relating to the consumption of contaminated shellfish (Trainer, 2002). HAB monitoring programs have traditionally been regulatory in nature, and not designed to determine temporal and spatial trends of HAB events (NFSC, 2012). Hence, long term datasets showing possible links to climate change are not available. Furthermore, it is difficult to separate the possible effects of climate change from anthropogenic impacts, particularly increased discharges of nutrients in developed coastal areas, sewage releases and ballast water introduction into the ocean.

The National Oceanic and Atmospheric Administration (NOAA) administers national interdisciplinary research programs to address HABs through a combination of regional ecosystem and targeted research approaches. For example, NOAA recently funded research in California, in partnership with the Southern California Ocean Observing System and Central and Northern California Ocean Observing System, which conduct HAB monitoring at regional pier stations (CeNCOOS, 2012; SCCOOS, 2012). Collaborators include University of California Santa Cruz, the University of Southern California, Moss Landing Marine Laboratory, Monterey Bay Aquarium Research Institute, the Southern California Coastal Water Research Project, University of California Los Angeles, and NOAA's National Centers for Coastal Ocean Science. The research will combine the detection and monitoring of HABs with ocean models that forecast ocean conditions to predict blooms. This capability will enhance the ability of California agencies to take action to protect public health and marine resources. (NCCOS, 2011).

The 2012 Climate Action Strategy being developed by the California Natural Resources Agency through the Climate Action Team (CAT) will include a "Coastal and Ocean" chapter which recommends strategies for adapting to coastal and ocean impacts of climate change, including those for protecting public health and the health of coastal and bay communities from harmful algal blooms (OPC, 2012).

VALLEY FOG

Anecdotal evidence suggests that Central Valley winters are less foggy than they were a few decades ago. Valley fog promotes colder temperatures during the winter, a critical factor for achieving a period of soil dormancy in agricultural regions. Recent analyses of wintertime temperatures show that "winter chill" has decreased by several hundred hours in California since the 1950s (see indicator, page 54). Scientists hypothesize that warming is causing winter chill accumulation in the Valley to decrease, and this trend is associated with a decline in the number of days and spatial extent of valley fog. This trend could have both adverse consequences—decreased yields in California's fruit and nut-growing regions—as well as benefits resulting from reduced energy use for heating in the Central Valley. Research is underway to analyze long-term trends in winter fog between November and February across the Central Valley using satellite imaging and climate data, and to estimate the effect of this trend on energy demand for heating (CEC, 2011).



Central Valley Fog, December 2, 2008
(NASA GOES satellite image)

FOREST DISEASES AND BARK BEETLE INFESTATIONS

Sudden oak death of tanoak on Mount Tamalpais, California (US Forest Service)

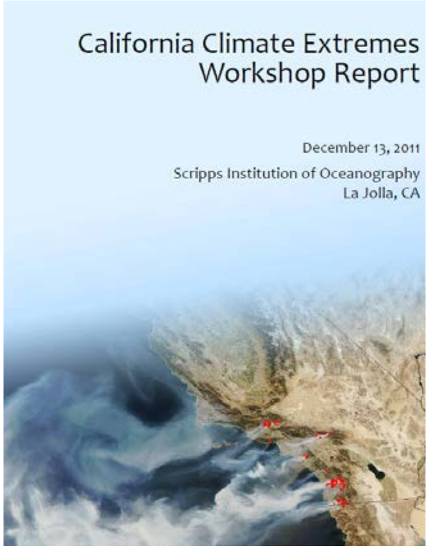
Climate change is projected to affect forest ecosystems in the Western United States by influencing the survival and spread of disease-causing pathogens as well as the susceptibility of the trees (USFS, 2011). Examples of diseases that may be influenced by climate change include foliar, stem rust, canker, dwarf mistletoe, root diseases, and yellow-cedar decline. Increases in temperature and changes in precipitation could alter stages and rates of development of a pathogen, modify host resistance, and lead to changes in the physiology of host-pathogen interactions. The most likely effects are changes in the geographical distribution of trees and pathogens and in tree mortality. Scientists note the following uncertainties when forecasting climate related diseases in forests: the degree of climate change; pathogen biology under changing climate; the effects of changing climate directly on the host; and interactions between the pathogen, host and climate.

In recent decades, billions of coniferous trees have been killed by native bark beetles in Western US forests, and several of the current outbreaks are among the largest and most severe in recorded history (Bentz et al., 2009). Climate change appears to be a factor driving in at least some of the current bark beetle outbreaks. Temperature influences everything in a bark beetle's life: the number of eggs laid by a female, the ability to disperse to new host trees, over-winter survival, and developmental timing. Shifts in precipitation patterns and associated drought can also influence bark beetle outbreak dynamics by weakening trees and making them more susceptible to beetle attacks. More frequent extreme weather events will likely provide abundant resources for some bark beetle species, creating the potential to trigger localized outbreaks (Gandhi et al., 2007). Fire, an important forest disturbance that is influenced by climate change (Westerling et al., 2006; see also *Large Wildfires* indicator, page 137), can reduce the resistance of surviving trees to bark beetle attack. A comprehensive synthesis of the direct and indirect effects of climate change on the population dynamics of bark beetles is lacking.

CHANGING PATTERN OF EXTREME EVENTS

An extreme climate event is one that has appeared only rarely in the historical record, such as a 1-in-100 year flood or a three-day heat wave that is hotter than 95% of all previous 3-day heat waves. As Earth's climate continues to change, climate extremes will change in intensity or frequency, or both (Pierce, 2012). The impacts of climate extremes will depend in large part on the degree of exposure and the vulnerability of human and natural systems (IPCC, 2012).

In the next few decades, it is likely that California will be faced with increased impacts from extreme events such as heat waves, wildfires, droughts and floods (Mastrandrea et al., 2009). Some extreme events have already very likely changed in frequency and intensity over the last several decades and these changes are expected to continue. Two of these extreme events—extreme heat events (page 48) and wildfires (page 137)—are discussed as climate change indicators in this report.



California Climate Extremes
Workshop Report

December 13, 2011
Scripps Institution of Oceanography
La Jolla, CA

In December 2011, at the California Climate Extremes Workshop, scientists presented what is known about extreme weather events in the state, and how they might evolve in a changing climate for the rest of the century (Pierce, 2012). Among the climate extremes discussed (that are not already described as climate change indicators in this report) were storms, floods and drought.

Long-term data are necessary to understand observed changes in the frequency of extremes. While climate scientists generally cannot directly attribute a particular event to global warming, it is very likely that several of the unprecedented extremes of the past decade would not have occurred without anthropogenic global warming (Coumou and Rahmstorf, 2012).

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APPENDIX A
CALIFORNIA'S EFFORTS TO ADDRESS CLIMATE CHANGE

California has a comprehensive strategy to address the risks climate change poses to the state's people and resources. By providing leadership on climate policy, the state is influencing policymaking and promoting solutions to the global challenge of reducing greenhouse gas (GHG) emissions. California's climate programs encompass ***mitigation*** of GHG emissions through a comprehensive set of policies and programs; ***adaptation*** strategies designed to reduce California's vulnerability to climate impacts and enhance the resiliency of communities, infrastructure, resources and people; ***research*** supporting the understanding of climate change and its impacts in the state; and ***joint action*** efforts through regional and international initiatives to expand emission reduction programs and enable effective adaptation (Cal/EPA, 2010). The Climate Action Team, a multi-agency group led by the Secretary for Environmental Protection, coordinates these activities (http://www.climatechange.ca.gov/climate_action_team/index.html).

MITIGATION

The California climate program has evolved through a series of statutory requirements and executive orders over more than 20 years. California established the first comprehensive program of regulatory and market mechanisms to achieve real, quantifiable, cost-effective GHG reductions with the enactment of the California Global Warming Solutions Act of 2006 (Núñez, 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, by Executive Order, Governor Arnold Schwarzenegger 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 California Air Resources Board (ARB).

In 2007, ARB adopted the Regulation for Mandatory Reporting of Greenhouse Gas Emissions in order to track progress in meeting GHG target levels pursuant to AB 32. The first mandated GHG reporting program of its kind in the United States, the regulation requires large emission sources to report their GHG emissions in 2008 and every year thereafter. The California statewide GHG Emission Inventory, developed by ARB, provides regulatory and policy staff with valuable information regarding the State's GHG emissions (http://www.arb.ca.gov/cc/inventory/inventory.htm). Beginning in 2009, approximately 600 California facilities were required to report their GHG emissions to ARB.

Pursuant to AB 32, ARB has developed a market-based Cap-and-Trade program for reducing GHG emissions. Under this program, an overall limit on GHG emissions from capped sectors will be established and facilities subject to the cap will be able to trade permits (allowances) to emit GHGs. The California Cap-and-Trade program began in 2012.

California is also participating in the Western Climate Initiative (established in 2007) along with Quebec, Canada. The Initiative is working towards consistent GHG reporting standards and is in the process of creating a GHG emissions trading market for North America.

Finally, the Sustainable Communities and Climate Protection Act of 2008 (SB 375), encourages better integration of transportation and land use planning in ways that reduce GHG emissions. SB 375 requires ARB to develop regional GHG emission reduction targets for passenger vehicles for 2020 and 2035 for each on the State's 18 metropolitan planning organizations (MPOs). Each MPO develops its own unique plan, known as a Sustainable Communities Strategy (SCS), for meeting its targets through a locally-driven process. The plans can include any combination of land use strategies, transportation system improvements, and transportation-related measures or policies developed at the local and regional level to meet the targets. Since transportation and land use planning has a significant influence on emissions from transportation sources, implementation of regional/community planning and transportation measures are imperative to manage and control the regional emissions.

Climate Change Policy Milestones

- 1992 *United Nations Framework Convention on Climate Change* aimed to achieve stabilization of GHG concentrations at a level that would prevent dangerous interference with the global climate system.
- 1997 *Kyoto Protocol* set targets for the reduction of GHG to approximately 5 percent below 1990 levels between 2008 and 2012.
- 2006 *California Global Warming Solutions Act* set a goal of reducing greenhouse gas emissions to 1990 levels by 2020.
- 2009 *U.S. EPA National GHG Emissions Rule* requiring annual GHG emissions reporting by large emission sources, upstream fuel providers, and engine manufacturers beginning in 2011.

ADAPTATION

With the growing recognition that climate change is already underway and science that suggests additional impacts are inevitable despite mitigation efforts, adaptation planning is rapidly becoming an important policy focus worldwide. In many states, efforts are beginning in nearly every sector of society, ranging from coastal planning for higher sea levels and reviews of water and drought management strategies, to climate-sensitive species preservation and habitat conservation planning, to providing cooling centers during heat emergencies. (CNRA, 2009)

California has already been experiencing rising sea levels, increasing average temperatures, more extreme hot days and fewer cold nights, shifts in the water cycle with less winter precipitation falling as snow and both snowmelt and rainwater running off sooner in the year. In view of this, the state is taking steps to prepare for and *adapt* to climate change and its impacts. Adaptation generally refers to efforts that respond to the impacts of climate change; it includes adjustments in natural or human systems to actual or expected climate changes. These adjustments are intended to minimize harm or take advantage of beneficial opportunities. (CNRA, 2009)

The California Natural Resources Agency (CNRA) coordinates the activities of a wide variety of state agencies in developing adaptation strategies through the California Climate Adaptation Strategy (http://resources.ca.gov/climate_adaptation/statewide_adaptation/). The strategy proposes a comprehensive set of recommendations designed to inform and guide California decision makers as they begin to develop policies that will protect the state, its residents and its resources from a range of climate change impacts. Adaptation strategies have been developed for the following sectors: agriculture, biodiversity, forestry, coast and oceans, public health, water, and energy and transportation.

A web-based climate adaptation planning tool called Cal-Adapt allows users to identify potential climate change risks in specific geographic areas throughout the state. Cal-Adapt provides California communities with information needed to begin planning for climate impacts. It can be accessed at: http://cal-adapt.org/blog/2011/jun/6/welcome-to-cal-adapt/.

RESEARCH

California has relied on a climate change research program to inform policy decisions. State-sponsored research has provided state-specific data, projections and assessments on climate change and its impacts.

The California Energy Commission’s Public Interest Energy Research (PIER) program is the state's premier energy research, development and demonstration program, advancing science and technology in energy-related fields (http://www.energy.ca.gov/research/index.html). PIER directed a large amount of research into the area of climate change by funding the creation of the California Climate Change Research Center in 2003 (http://sio.ucsd.edu/cccc/ and http://www.energy.ca.gov/research/environmental/climate.html). The center—the first major state-sponsored research institution in the country—organizes core research activities at the University of California (UC) at San Diego’s Scripps Institution of Oceanography and at UC Berkeley. Its work is complemented by efforts at other research institutions, including many UC campuses and laboratories. The broad scope and effectiveness of the PIER climate change program is well-known nationally and internationally. PIER has been vital in making California a leader in climate change vulnerability and adaptation planning for climate change, ahead of other states and other countries.

A working group of the Climate Action Team coordinates research performed or sponsored by PIER and other state agencies. In addition, the *Research Working Group* is tasked with identifying research gaps and opportunities for collaboration and providing a forum for discussing future climate change research priorities (http://www.climatechange.ca.gov/climate_action_team/research.html).

Climate change research projects and programs taking place in California, particularly projects or programs receiving federal funding, are catalogued in the *California Climate Change Research Database*, a project of the ARB and California Council on Science and Technology (http://californiaccresearch.org/). The database includes a wide range of projects including research on air quality/atmospheric chemistry, climate change over time and the impact of climate change on the ecosystem and biodiversity.

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APPENDIX B.

NORTH PACIFIC OCEAN CONDITIONS AND PROJECTIONS FOR CLIMATE CHANGE

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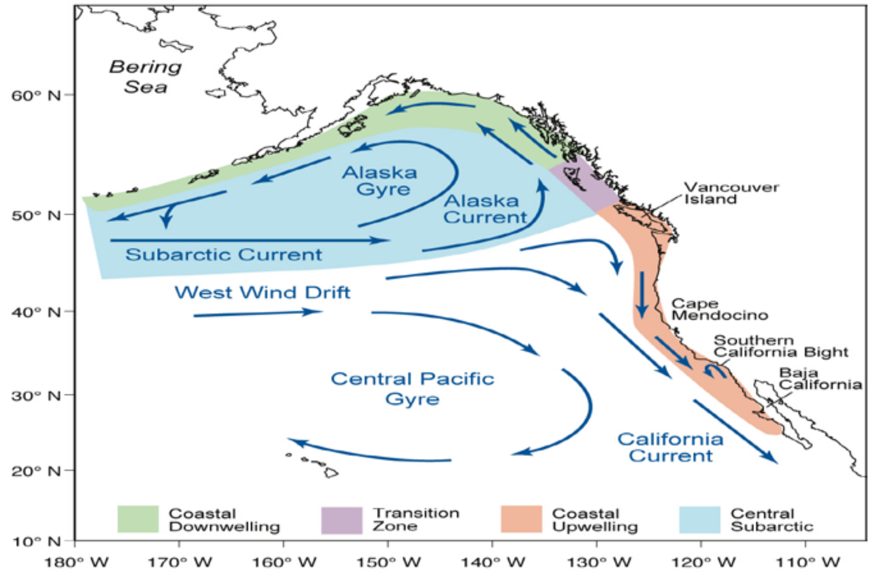
The Pacific Ocean influences California's mild, Mediterranean climate. Temperature and precipitation patterns for much of the state, including the cool wet winters and warm dry summers flavored with coastal fog, are determined largely by ocean conditions. Even the weather in the Sierras and over much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

Figure 1. California Current



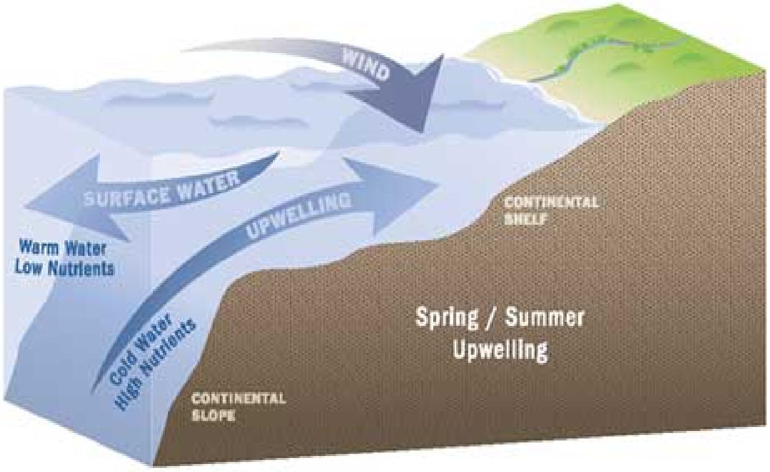
Source: J.A. Barth, Oregon State University, 2007

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).

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.

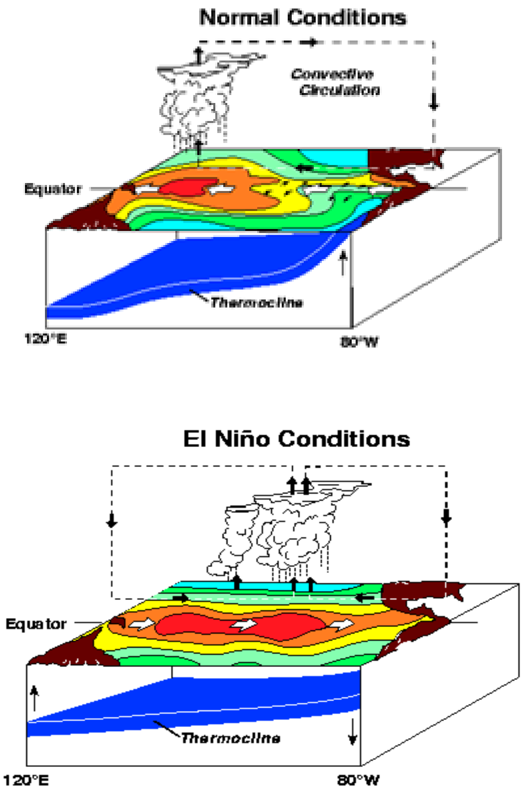
Another factor that influences upwelling is vertical stratification, which is a measure of the increase in water density with depth. Higher stratification represents a greater contrast between the less dense (warmer, fresher) surface water layer and denser (cooler, more saline) deep water; greater wind 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



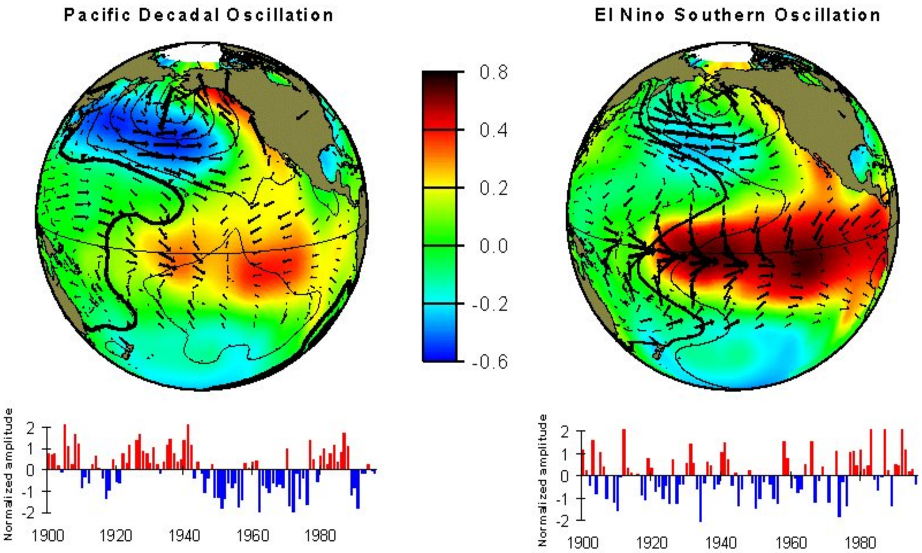
El Niño events occur irregularly at intervals of two to seven years, with the strongest events occurring about once per decade (1941-42, 1957-58, 1965-66, 1972-73, 1982-83, 1986-87, 1997-98). They typically last 12 to18 months, peaking along the coasts of North and South America around December (hence 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

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

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.

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 (2007d) 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, 2007d). 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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