California Climate Extremes Workshop Report

December 13, 2011

Scripps Institution of Oceanography
La Jolla, CA

Acknowledgements

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California Climate Extremes Workshop Report

13 December 2011

Robert Paine Scripps Forum for Science, Society, and the Environment
Scripps Institution of Oceanography
La Jolla, California

Edited by David W. Pierce
Scripps/UCSD

Contents

Preface

It is a pleasure to introduce this report prepared by some of the leading climate scientists in California. This report summarizes the main findings of a workshop organized to present what is known about extreme weather events in California and how they would evolve in a changing climate for the rest of this century. The presenters offered this information in a format that was accessible to decision makers, scientists from different disciplines, and the public in general. High-level officials from State Government were present, including representatives from the Governor's Office. Given the high praise offered by all the participants, including myself, I can safely conclude that the scientists were able to successfully convey their messages about the importance of preparing for extreme weather events that will be accentuated by global climate change. The summary talks from this workshop presented at the Governor's Conference two days later were equally effective.

California has a long tradition of supporting regional climate change research, starting in the late 1980s with a mandate by the Legislature to investigate the potential impacts of climate change on our economy and natural resources. More recently, the California Energy Commission's Public Interest Energy (PIER) Program has been directing and supporting research that has been influential in policy circles. These efforts do not happen in a vacuum. Federal agencies have been instrumental in providing research support for California and have collaborated with us for a long time. We owe a special thanks to NOAA's California Nevada Applications Program, our invaluable partner since the early 2000's.

In times of tight budgetary constraints, state and national level policy leaders must remember the need for long term strategies that will be essential to answer practical resource management questions of today and for future generations. This workshop substantially contributed to this understanding and further advanced the link between science and policy in California.

James Boyd

Vice-Chair
California Energy Commission

What is an extreme climate event?

All extremes are relative to some expectation. An extreme climate event is one that has appeared only rarely in the historical record, which goes back about 100 years. For example, a 1-in-100 year flood is an extreme event, as is a three-day heat wave that is hotter than 95% of all previous 3-day heat waves.

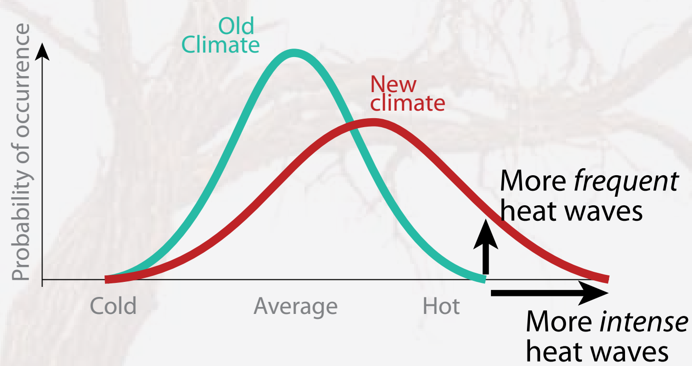
As Earth's climate continues to change, the climate extremes we experience will alter in potentially different ways. The *intensity* could change, or the *frequency* (or both).

Some extremes could become more *intense*. Intensity refers to how different the climate extreme is from normal conditions. For instance, as the climate warms, heat waves will likely become hotter than any seen since measurements began.

On the other hand, some extremes could change their *frequency*, which is to say, how often they occur. Flooding will probably become more frequent in the future as warmer conditions mean some snowfall from winter storms in the Sierra Nevada converts to rainfall, and the snow on the ground melts earlier in the year.

Together, the frequency and intensity of weather events make up a *distribution*. The well-known bell curve is an example of a distribution. Extreme events are those that fall on the ends of the distribution. One of the tasks of climate science is to understand how the distribution of climate events is likely to change in the future.

Understanding how the frequency and intensity of extremes changes in the future has implications for how we could adapt to those changes. For instance, if flooding becomes more intense (a larger volume of floodwater), bigger flood control channels may be needed. If flooding becomes more frequent, perhaps more small channels needed to drain roads that inconveniently flood during heavy rains would be needed instead.



As the climate changes, the distribution of events such as heat waves and floods will change. Extreme events are those on the tails of the distribution, and could change in their intensity (for example, how hot a heat wave is) or their frequency (how often the event occurs). After IPCC (2001), Fig. 2.32.

Want more information?

California specific: "Our Changing Climate: Assessing the Risks to California": http://meteora.ucsd.edu/cap/pdffiles/CA_climate_Scenarios.pdf

The whole Earth: Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report: http://ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

Executive Summary

The California Climate Extremes workshop brought together diverse experts from the physical, biological, social, and economic sciences. Yet the talks showed that there are common themes of impacts running throughout these multifaceted subject areas.

Water is a common element to many of the extreme impacts, through the effects of droughts, floods, and sea level rise. A possible decline in reliability of surface or ground water was cited as an area of concern by farmers, and an economic analysis explored the implications of changes in water delivered to the Central Valley. Floods affect aquatic ecosystems and have enormous economic impacts; over the period 1993-2007, floods generated more insured losses to California farmers than any other type of weather related disaster. Sea level rise coupled with coastal storms will have many impacts, including damage to coastal energy infrastructure.

California is right to be concerned about both flooding and droughts. Three-day precipitation accumulations in California can be as large as anywhere in the U.S., including the Gulf Coast states. For example, in the winter of 1862 storms pummeled the state for weeks, causing widespread flooding and monumental damage. A similar event could cause a half trillion dollars in losses if it occurred today. On the other hand, California's history is marked by extensive drought, and unlike the Columbia and Colorado basins, California has a limited amount of reservoir capacity to carry it through multi-year dry spells. Southern California imports the majority of its water, and a warmer climate is likely to spur longer and deeper droughts in the Colorado River source water regions.

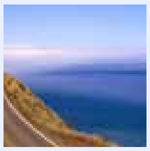
Heat waves are another cross-cutting element, and are likely to become more intense and frequent, especially along the coast. More humid nighttime heat waves and the higher ozone production that generally accompanies heat waves are likely to affect Californians' health. Natural ecosystems and current strains of crops such as corn, soybeans, and cotton are sensitive to temperature extremes, with many crops showing a gradual increase in yield with mild warming that quickly transitions to a steep decline once a threshold temperature is passed. These non-linear effects of climate change are critical, yet have not always been taken into account when calculating the economic impact of climate change.

Wildfire and energy are two other themes that intersect with many application areas. Fires directly affect transmission lines, and transmission lines can cause wildfires, as is being considered in lawsuits over the destructive 2007 wildfires in Southern California. Smoke and other air pollution from wildfires affects human health, and although some ecosystems have become adapted to (and rely on) wildfires, the increasing frequency of fires as the century progresses could have detrimental effects.

A brief summary of each application area is given on the next page.

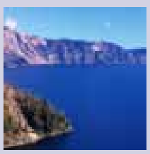
Heat Waves and Storms

As temperatures warm in coming decades, heat waves will increasingly be characterized by hot, humid nights. Storms are likely to shift north, and winter storms in the mountains will drop more rain instead of snow. Stanta Ana winds are likely to decline in frequency and wind speed but become hotter and drier. Colorado River water could decline.



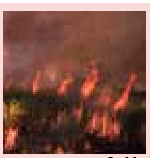
Sea Level Rise

Sea level will likely rise 3-5 feet this century as the oceans warm, seawater expands, and ice caps melt. The danger is when this is combined with high tides, storm surges, and regional sea level increases due to El Niño. There will be more bluff erosion, progressively greater flooding followed by inundation, and beach retreat later in this century.



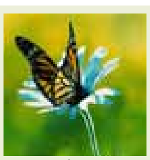
Reservoir Management

Water users want a steady and reliable water supply, but climate extremes and variability make this difficult. Right now, California's reservoirs are managed with fixed rules based on history. The INFORM project demonstrates that adaptive management policies, using the best available forecasts and modern decision science, can do better.



Wildfire

Wildfires cause deaths, property damage, and air pollution. As the climate changes and summers become hotter and drier while winter snowfall melts earlier, seasons with many large fires are likely to increase 10-fold or more. Thinning undergrowth, building practices, and the amount of development in the wildland-urban interface affect losses from fire.

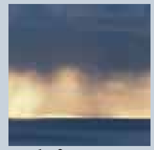


Plants and Animals

As the climate changes and ecosystems shift in response, relationships between interconnected species will be altered, putting additional stresses on species. Droughts cause saltwater intrusion in estuaries, floods deposit silt on fish eggs, and heat waves can kill birds and chicks. Some species are adapted to fire, but could be harmed if future fires increase.

Economics

Extreme climate events will likely dominate total economic losses from climate change. There are threshold effects — larger climate extremes cause proportionally much greater damages — which have not always been included in economic evaluations of climate change. When thresholds are included, extreme events are the main driver of losses.



Water Supply & Flooding

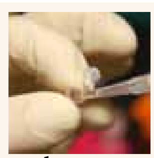
Sierra Nevada snowpack is likely to decline by 50% or more, with more winter rain instead of snow. This could drive bigger floods. California gets nearly half its precipitation from a few big storms driven by "atmospheric rivers" with moisture from the Pacific; if a winter storm fed by an atmospheric river stalled over California, it could cause $500B damage.

Coastal Flooding

Sea level rise and extreme winter storms could combine to produce more extensive coastal flooding than previously seen. If no changes are made, by the end of this century a large storm could inundate key roadways in the San Francisco area, increasing the East-West commute time by a factor of 2 to 10 and making some interchanges inaccessible.

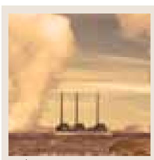
Agricultural Impacts

Vulnerability to climate varies widely across the state, depending on how much water crops use and how variable local precipitation is. More diverse crops could increase resiliency but are costly to implement. Future water availability is farmers' top environmental concern, and could be addressed by growth policies and irrigation technology.



Human Health

Heat waves kill people, primarily through cardiovascular diseases. Hot days also cause more ozone to form, which is associated with asthma attacks, sick days, and emergency room visits. The 2006 California heat wave killed ~400-650 people and caused about $5.4B in damage. As the climate warms, heat waves will become longer and more frequent.



Energy

Heat waves drive peak power use, fires affect power lines, and sea level rise will likely impact coastal energy infrastructure. As the climate warms and people install more air conditioners, the extra increment in energy demand on the hottest days is likely to grow by ~20%. Climate change by itself could increase residential energy consumption notably.

Barriers to Adaptation

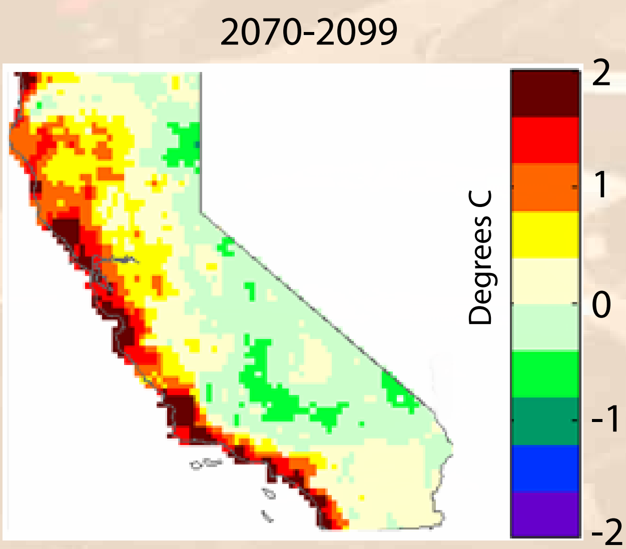
The biggest barriers to implementing adaptation plans are institutional, motivational, and economic. Lack of time, staff, and technical expertise are also problems. Local leadership is key to overcoming these barriers, which are often local in origin. Integrating adaptation into the regular community or coastal planning cycle is often a way to move forward.

Heat waves and Storms

Alexander Gershunov

"Heat waves may become more intense, even relative to the warmer average."

In coming decades daily high temperatures will rise, and more heat waves will be characterized by hot, humid nights. Along the coast, where the ocean tends to keep the air cooler, the intensity of heat waves might increase as the marine layer adjusts to the new climate. Nevertheless, cold days and months will still be experienced, just not as frequently. Warmer air can hold more moisture, so storms could generate more precipitation. But storms are likely to shift northward, becoming less frequent in the southern half of the state, and winter storms in the mountains will drop more rain instead of snow. Santa Ana winds are likely to become less frequent and decline in wind speed, but hotter and drier. More water lost to evaporation will affect the water supply for Southern California.



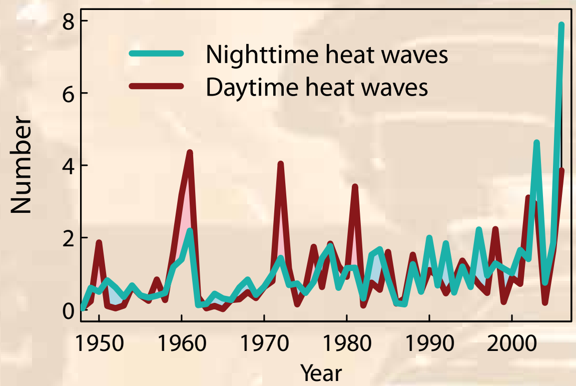
This map doesn't show the average warming expected in California; instead it shows how much warmer *extreme* hot days will be relative to the new, warmer average temperatures in the state. This difference between average and unusually hot summer day is likely to increase by several degrees along the coast (orange and red areas). In other words, not only will the state warm on average, but hot extremes are likely to become more intense along the coast as well. This may be related to changes in the coastal marine layer in the future. From A. Gershunov and K. Guirguis, Scripps Institution of Oceanography.

As human-produced greenhouse gases accumulate in the atmosphere, the climate will continue to warm. However the warming will vary across California and in different seasons. Warming will likely be greatest in summer and in California's rapidly developing interior. It will likely be least in winter and along the coast.

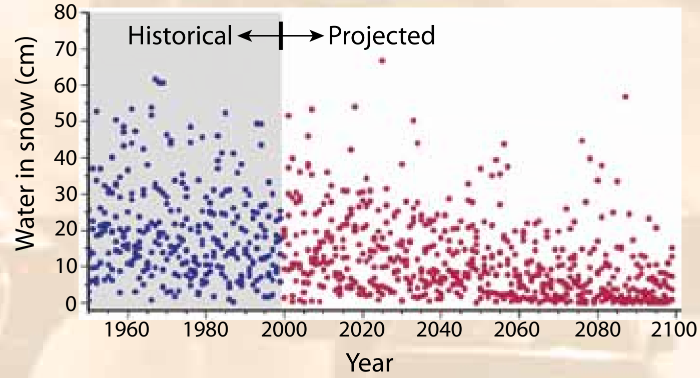
Historically, California's heat waves have been characterized by hot days that cool off at night. This is likely to change, as the nights become hotter and more humid. This change is detrimental to human health, as both temperature and humidity contribute to a greater heat stress. The shift toward more humid, nighttime-dominated heat waves has been seen in the observations over the last 60 years, and is predicted to accelerate in the coming century.

Temperatures along the coast are moderated by the cool ocean water, especially in summer. A humid, often cloudy or foggy marine layer frequently forms along the coast, reducing the daily high temperatures. As interior temperatures go up, intermittent lapses in the marine layer may mean that heat waves right along the coast will become proportionally more extreme. Most of California's population is clustered along the coast, so this could affect both human health and energy use.

More hot days is not the only issue facing California. A loss of cold days has implications as well. Some economically important fruit and nut crops grown in California require enough hours of cold temperature to produce the crop. This is traditionally measured in the number of hours experienced below a threshold, such as 45 °F. The number of these "chill hours" will decrease, potentially affecting crops, but unprecedented



Over the past 60 years, heat waves are increasingly coming as hot, humid nights (blue) rather than only hot days (red). Projections show this trend accelerating in the coming century. Redrawn from Gershunov et al. (2009) *J. Climate* v. 22 p. 6181.



California relies on the mountain snowpack to store water from winter storms. As temperatures warm in the future (red), more snow will fall as rain, and what does fall as snow will melt earlier, reducing this natural storage of water in the snow. After Cayan et al. (2011) *Proc. Nat. Acad. Sci.* v. 107 p. 21271.

cold conditions will still occur even as the climate warms. As a result, in some locations, the overall temperature variability will increase.

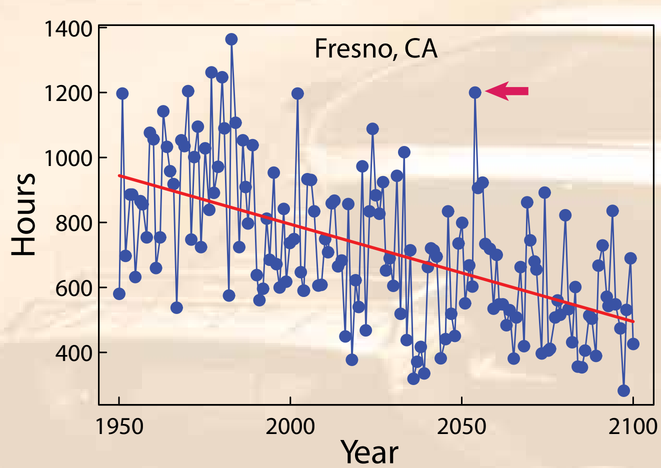
Precipitation

The amount of water vapor in the air will increase as temperatures warm, potentially leading to heavier rainfall events. However, storm tracks will also shift northward over California, reducing the frequency of storms in the South. Between these competing effects, the overall amount that precipitation will change is hard to quantify, especially since precipitation varies so much year to year.

A bigger effect than changes in the amount of precipitation will be the transition from snow to rain in the mountains as the climate warms, an effect that has already been observed. California relies on snowpack as a natural reservoir storing winter storm water, and this storage will decrease in the future. California might need to consider changes to its water infrastructure to compensate, yet such changes can be expensive and politically contentious.

Increasing temperatures also drive more water loss from plants and the soil, which will increase the intensity and duration of droughts in the American Southwest. Southern California imports a substantial part of its water supply from regions where available water is likely to decline. Extreme Southwestern droughts are likely to become more intense as temperatures rise.

Finally, Santa Ana winds can contribute to devastating wildfires. Santa Anas are generated from a cool, dense pool of air in the interior, which compresses and heats as it flows downhill through mountain gaps towards the coast. Santa Anas are likely to decrease in frequency and average wind speed, but become hotter and drier in the future.



The number of chill hours in a year, which fruit and nut plants need to germinate, is likely to decline. Yet cold extremes will still be experienced (red arrow). Redrawn from Baldocchi & Wong (2008) *Climatic Change* v. 87 p. S153.

Contributors: Alexander Gershunov (Scripps/UCSD), Michael Dettinger (USGS), Edwin Maurer (Santa Clara Univ.), Michael Mastrandrea (Stanford University),Alex Hall (UCLA), Norm Miller (LBNL), Lisa Sloan (UC Santa Cruz), Kelly Redmond (WRCC/DRI), Guido Franco (CEC), Robin Webb (NOAA), David Pierce (Scripps/UCSD), Daniel Cayan (USGS and Scripps/UCSD), Kristen Guirguis (Scripps/UCSD)

For more information:

Gershunov, A., et al. (2009): The Great 2006 Heat Wave over California and Nevada: Signal of an Increasing Trend. *J. Climate* v. 22 p. 6181.

Water Supply & Flooding

Marty Ralph

"We need to recognize there is huge risk here."

Water from winter storms is stored in the Sierra Nevada snowpack, which is likely to decline 50% or more by the end of the century as winter storms drop more rain instead of snow. This could also drive bigger floods. California gets nearly half its winter precipitation from a few big storms driven by "atmospheric rivers" carrying water vapor from the Pacific; the intensity of atmospheric rivers will probably increase in coming decades. If a winter storm fed by an atmospheric river stalled over California — an event that has happened in the past — it could cause $500B of damage. These risks could be reduced with better offshore monitoring of big storms, improved forecasts of snowpack and runoff, and reservoir management that takes precipitation and runoff forecasts into account.

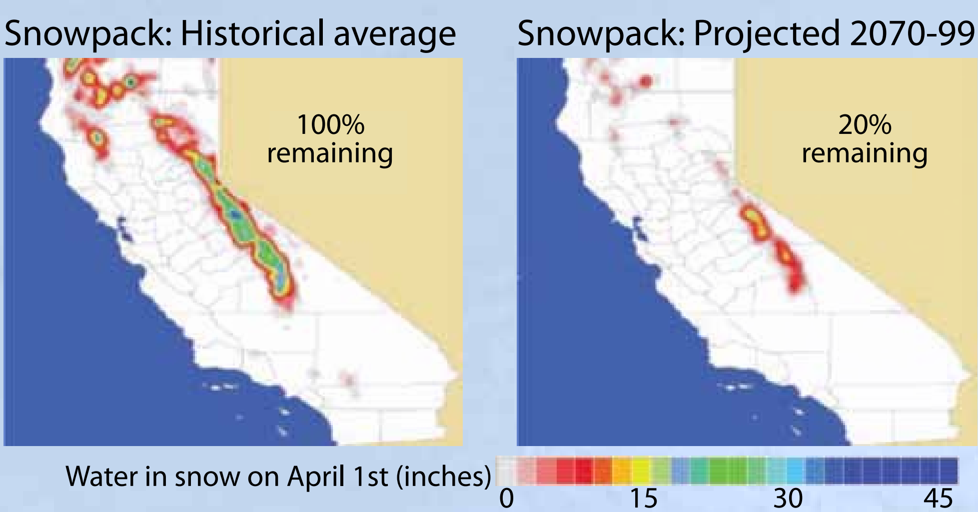
California's water supply is fed by winter storms in the Sierra Nevada, imports of Colorado River water to Southern California, and large-scale transfers of water from the Northern to Southern part of the state. All these could be affected by extreme climate events. For example, water is transferred to the South through the Sacramento/San Joaquin delta region, where the levees are subject to subsidence and vulnerable to sea level rise or an earthquake.

The Sierra Nevada snowpack forms an integral part of California's water supply, buffering the effect of large winter storms by holding their precipitation until the snow melts later in the year. Warming temperatures mean that the snowpack will melt earlier, and more winter precipitation will fall as rain rather than snow. Between these effects, California might lose half its snowpack by the end of this century. Flooding would be worsened since rain can runoff quickly compared to snow.

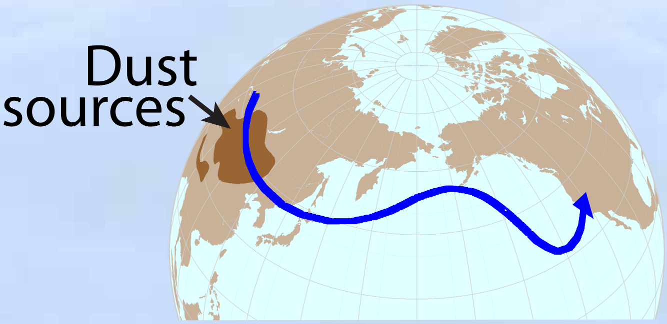
California averaged $370M per year in flood damage over the period 1983-99 (equivalent to $550M/yr today), the third highest flooding losses in the nation. California is vulnerable to floods because the storms that hit the state are as big as any in the country in terms of the total precipitation over 3 days.

The amount of precipitation dropped by storms might be influenced by dust particles in the air. Satellites and models of air movement show that these dust particles can originate in Asia, and are carried to California by high altitude winds. Dust and soot of Asian origin that fall on California's snowpack can also make it darker, which means it absorbs more heat from the sun and melts earlier. These connections between Asian dust and California's snowpack are currently being researched so they can be better understood.

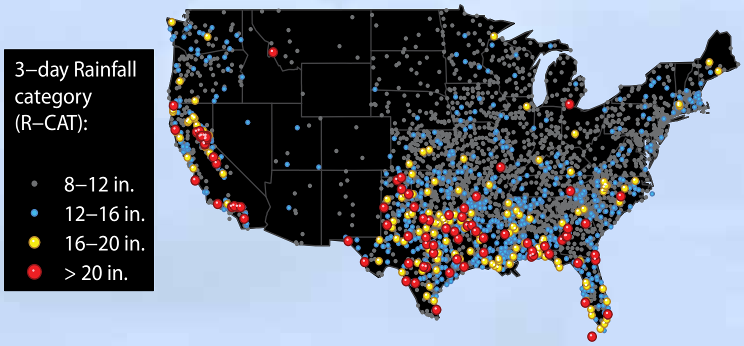
An extreme drought in the Southwestern U.S. would affect California by reducing how much Colorado River water is



California relies on snowpack in the Sierra Nevada as a natural water reservoir. By the latter part of this century, 80% of the snowpack on the first of April (typically around the peak depth) could disappear. From *Our Changing Climate: Assessing the Risks to California* (2006), CEC Report CEC-500-2006-077.



Asian dust and soot can be carried to California by high altitude winds, and affect how much precipitation local storms produce. Dust and soot can also darken snow, making the snow absorb more heat from the sun and causing it to melt earlier in the spring. Redrawn from Ault et al. (2011) *J. Geophysical Research-Atmos.* v. 116 p. D16205.



California storms can drop as much precipitation in three days as found anywhere else in the country, giving damaging floods. Redrawn from Ralph and Dettinger (2012), *Bulletin of the American Meteorological Society*, DOI: 10.1175/BAMS-D-11-00188.1.

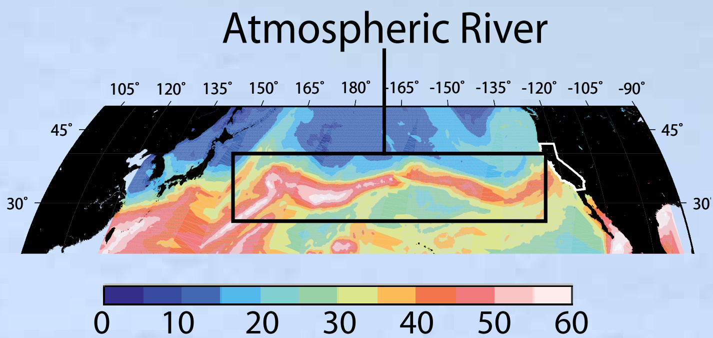
available for import. Climate projections indicate that such droughts will become more likely in the coming century. However, how much this would affect California depends on the way complex legal agreements between the water-using states might play out in the face of an extreme drought.

Atmospheric Rivers

About 35-45% of California's annual precipitation arrives in storms driven by a few "atmospheric rivers", filaments of exceptionally moist air that stream out from the tropics. The average atmospheric river carries 7.5 times as much water as the Mississippi River. Certain wind conditions carry this moisture to California, where it can fall in a deluge that causes flooding when the atmospheric river is strong and stalls over saturated soils. The recent "ARkStorm" study focused on the consequences of such a storm stalling over California, as has happened before. It concluded that damages could exceed $500B were this to happen today.

Mitigating Risks

In hurricane-prone regions of the U.S. storms are observed offshore so communities can be prepared; a similar program could help California. Installation of an improved land-based observation system has already begun. In the Central Valley, a new flood protection plan takes sensible steps that could be applied in other areas: assessing vulnerabilities, identifying the climate conditions that could trigger losses, and estimating the likelihood of those events. Better storm and runoff predictions could be used in flooding estimates and in reservoir management, which currently uses fixed rules without considering weather forecasts. Finally, Asian dust is not included in forecast models, yet might influence how much precipitation a storm generates. Forecast methods and warnings focused on atmospheric rivers, and including dust, could improve predictions of rain or snow. This is especially important for extreme events, which is one of the greatest forecast challenges today, and a focus of NOAA's Hydrometeorology Testbed activities in California.



Colors show the amount of water vapor in the atmosphere (mm) measured by satellite. On this day (October 13, 2009) an atmospheric river was carrying tropical moisture to California, resulting in more than 15 inches of rain in Central California. Redrawn from Ralph et al. (2011), *Eos (Transactions of the American Geophysical Union)* v. 92 p. 265.

Contributors: Marty Ralph (NOAA), Michael Hanemann (UC Berkeley), Ben Brooks (U. of Hawaii), Michael Dettinger (USGS and Scripps/UCSD), Daniel Cayan (Scripps/UCSD and USGS), Konstantine Georgakakos (HRC), Jay Lund (UC Davis), Jay Famiglietti (UC Irvine), Michael Anderson (CA Dept Water Resources), Jeanine Jones (CA DWR), Kim Prather (Scripps/UCSD).

For more information:

Dettinger M. D., et al. (2012): Design and quantification of an extreme winter storm scenario for emergency preparedness and planning exercises in California. *Nat. Hazards* v. 60 p. 1085-111.

Sea Level Rise

Gary Griggs

"Long term, beaches will begin to retreat, particularly where their back edges are fixed."

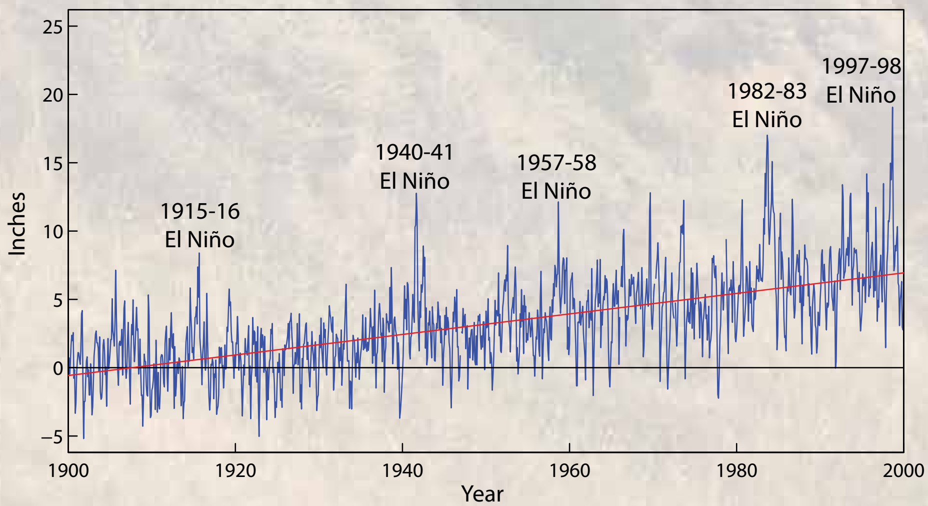
Sea level will rise as the Earth warms, seawater expands, and ice caps and glaciers melt. How much rise we will get is uncertain, but projections are for 3 to 5 feet in the coming century. The danger is when this sea level rise is combined with high tides, storm surges, and regional sea level increases due to periodic El Niño events. Even now, we experience coastal damage during severe storms; with sea level rise, there will be more bluff erosion, progressively greater flooding followed by inundation, and seasonal loss of beaches followed by beach retreat later in the century.

Naturally occurring episodic events such as tides, storms, and El Niños can affect sea level along California's coast in addition to the effect humans have on the climate. Strong El Niños temporarily raise coastal sea level by about a foot, while tides and storm surges change the local sea level by up to several feet. In the past, California has experienced coastal flooding and property damage when these factors combined. For example, in the winter of 1982-83 we experienced a strong El Niño plus a string of storms that hit the coast during high tide, causing over $200M in damage.

Another natural climate fluctuation, the Pacific Decadal Oscillation, affects California's sea level as well. In recent decades this Oscillation has suppressed sea level rise along the coast. When it inevitably reverses from natural causes, sea levels will probably rise faster than has been seen in recent years.

As the Earth's oceans warm in coming decades seawater will expand, and additionally the amount of water in the oceans will grow as glaciers and ice caps melt. Both will make it ever more likely that the high waves associated with winter storms will cause property damage along the coast.

There are many places along California's coast that are vulnerable to bluff erosion. For example, the Devil's Slide region near Pacifica has experienced numerous failures, at different times wiping out railroad tracks and part of Highway 1. Torrey Pines State Natural Reserve in San Diego County has had multiple collapses, and the nearby National Marine Fisheries Service building is being rebuilt farther inland for this reason. Numerous other buildings have been damaged in coastal communities such as Solana Beach, Encinitas, Santa Barbara, Capitola, Santa Cruz, and Pacifica. In Seacliff Beach State Park in Monterey Bay, a succession of eight sea-



Sea level measured at San Francisco shows a long-term rise over the last century, along with shorter term fluctuations from storms and El Niños. The worst damage to California's coast occurs when these factors combine, with storms and high tides occurring during an El Niño. Sea level rise is likely to be appreciably greater in the 21st century.

Magnitude of Consequence	Probability / Likelihood of Occurrence: Low	Moderate	High	Very High
High	• Massive release of methane and CO_2 from ocean • Asteriod impact			• Sea level rise with associated inundation and damage
Moderate		• Earthquake and tsunami		• Coastal cliff erosion • Large ENSO events combined with large waves
Low			• Large coastal landslides	

Risk between 2050 and 2100
Risk = Probability x Consequence

The risk an event poses is determined by both its likelihood and impact. By the end of this century, sea level rise will be both very likely and have a high impact on California's coast (red).

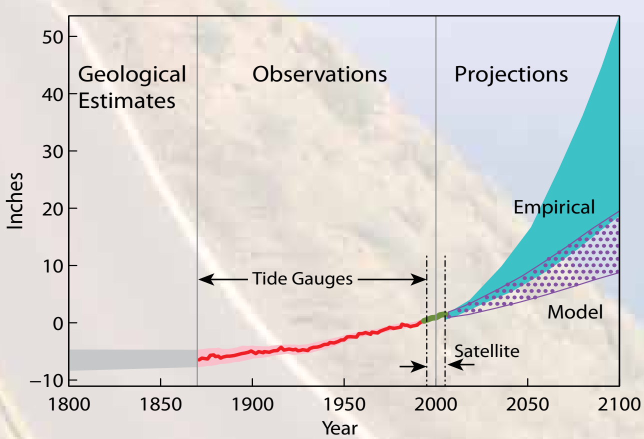
The Devil's Slide area near Pacifica, CA (south of San Francisco) shows remnants of a destroyed rail line, as well as modern California Highway 1. The area has experienced repeated sliding over the years. Photo copyright (C) 2002-2012 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

walls has been built over the years to prevent erosion; each one was eventually inundated and destroyed.

Looking Forward

Since 1993, sea level has been rising about 1/8" per year. That rate will almost certainly increase in the future, since greenhouse gases are accumulating in the atmosphere at an ever greater rate. Because water can absorb so much heat and carbon dioxide stays in the atmosphere for centuries, even if humans ceased all production of greenhouse gases immediately (an unlikely prospect) the oceans would continue to warm and expand for decades to come.

The last round of sea level projections from the Intergovernmental Panel on Climate Change (IPCC), completed in 2007, neglected melting glaciers and ice caps. It was felt at the time those processes were too uncertain to include.



Past sea level is estimated from geological evidence and tide gauges. It currently is measured by satellites. Future projections can use models (purple), which are known to be incomplete, or historical associations between past temperature and sea level (blue). After IPCC (2007) FAQ 5.1.

Since then, researchers have examined how past temperature changes affected sea level. If these historical relationships continue into the future, we are likely to have 3 to 5 feet of sea level rise in the coming century. One of the biggest factors in that uncertainty is what steps, if any, nations take to reduce greenhouse gas emissions. The next IPCC report, due in 2014, will include the effects of retreating glaciers and melting ice caps and will likely refine current estimates of sea level rise.

Given variability in storms and El Niños, and the uncertainty in projected sea level rise, we should continue to monitor key environmental conditions such as local sea level, wave heights, cliff retreat, and beach widths. That information, combined with the best sea level rise estimates we have available, will help us adapt to future changes in California's valuable coastal environment.

Contributors: Gary Griggs (UC Santa Cruz); Peter Adams (U Florida); Peter Bromirski (Scripps/UCSD); Daniel Cayan (Scripps/UCSD and USGS); Reinhard Flick (CA Dept. Boating and Waterways and Scripps/UCSD).

For more information:

Griggs, G. B. (2010): Introduction to California's Beaches and Coast. University of California Press, Berkeley, CA. 311p.

Griggs, G.B., K. Patsch and L.E. Savoy (2005): Living with the Changing California Coast. University of California Press, Berkeley, CA. 540p

Coastal Flooding

Greg Biging

"1-in-100 year extreme events could occur annually by 2050."

John Radke

"Flooding could isolate neighborhoods. Or, we can rethink our planning."

Sea level rise and extreme winter storms could combine to produce more extensive coastal flooding than we have seen before. This would have a major impact on transportation infrastructure in the San Francisco Bay area. If no changes are made, by the end of this century a large storm could inundate key roadways, increasing the East-West commute time by a factor of 2 to 10 and making some freeway interchanges inaccessible when flooding occurs. North-South travel is generally less affected. In some places, flooded access roads could make neighborhoods inaccessible to emergency crews.

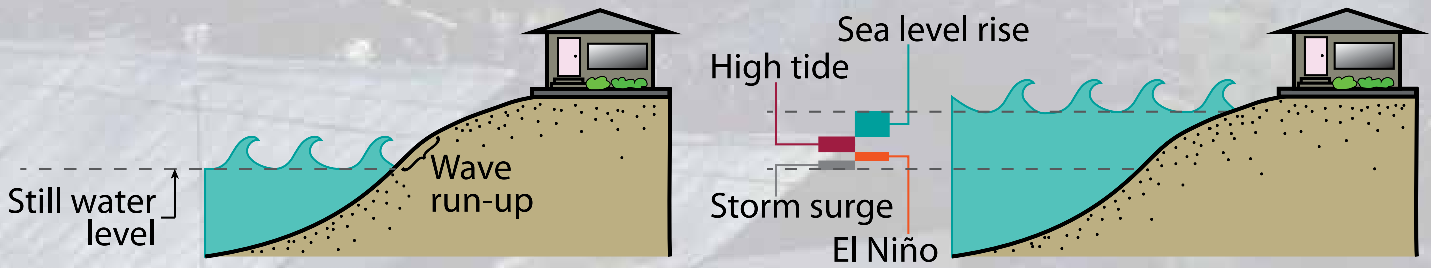
Bay Area freeways would be heavily impacted by an extreme winter storm occurring with the sea level rise we will experience later this century. Red dots show inaccessible interchanges; dotted lines show lost connections. Orange and red lines show that the east-west commute time could increase by a factor of 4-10. North-South routes are less affected. From Biging et. al (2012) forthcoming CEC report.

California has 1100 miles of shoreline, much of it developed. Beaches, marinas, ports, and coastal roads are important to California's economy, and historically, real estate near the coast has been some of the most expensive in the state.

Most sea level records show an upward trend over the last century, and that is expected to accelerate in coming decades. Increasing sea level means that waves generated by major winter storms can penetrate further up the beach or shore. Simulations of future climate suggest that wave heights might decrease somewhat along California's coast, but this will be more than made up for by the higher sea level.

The San Francisco Bay area is a natural place to study the effects of coastal flooding, since it has a dense population and critical coastal infrastructure that will be greatly affected by sea level rise. The effect of extreme flooding events on the Bay Area's transportation network can be examined with high resolution digital maps of the elevation of roadways, bridges, interchanges, and buildings. These maps are created by sensitive airborne instruments that measure the round-trip travel time of a laser pulse between the aircraft and the surface. Different simulated levels of sea level rise and winter storm activity can then be applied to the transportation system.

In some locations, such as the San Francisco airport, levees are used to reduce the chance of flooding. However the levees would be overtopped by peak water levels (sea level plus



Left: Still water level (SWL) has wind waves and tides averaged out. Wave run-up along the beach or coast carries water farther inland. Right: Sea level will likely rise by 3-5 feet in the coming century. The biggest damage from sea level rise will occur when high tides occur at the same time as storms and El Nino, all of which temporarily raise water levels.

storm surge plus waves) of eight and a half feet. Expanding the levees into the sensitive ecosystems of the Bay would be expensive and likely controversial.

In some locations, coastal flooding would greatly increase the time that first responders (police, fire, or medical personnel) would need to reach a location. Likewise, simulations show that East-West commute times in the Bay Area would increase by a factor of 10 during a peak storm event taking place atop high tides and sea level rise. The North-South transportation corridors are generally more redundant, and less affected by flooding.

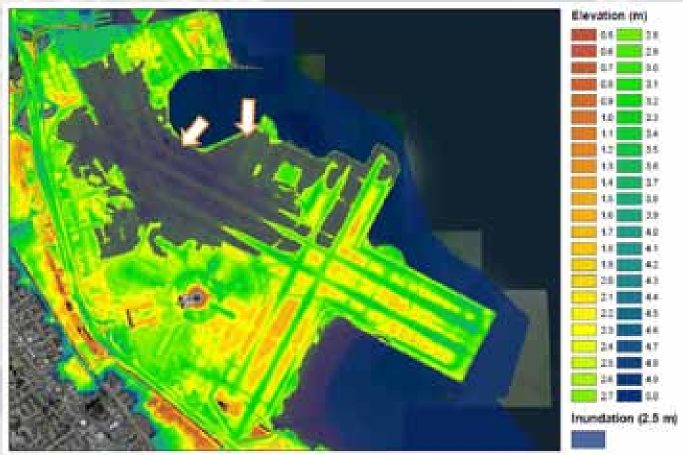
These problems could be mitigated by a change in how we think of planning transportation corridors. The cost will not necessarily be greater, but keeping rising water levels in mind as projects are planned and built could avoid some of the worst impacts of flooding on transportation connectivity.

Low-lying areas farther from the coast may flood, not from overtopped levees or waves that advance inland, but by storm water drains backing up and flooding areas from the inside. Local effects are also important. For example, wind-driven waves can build up over various distances in the Bay during storms, and this can have an impact on local shoreline overtopping and flooding. Understanding the local wind-wave climate is critical to determining the ultimate effects on local property and infrastructure.

Where to go from here

To address these problems we need:

- Advanced hydrologic modeling to understand how the levees, seawalls, storm surge, and waves interact
- An inventory of levees, shoreline protections, and storm drainage systems along California's coast
- A better understanding of how these processes could affect Sacramento, the San Joaquin delta region, and other coastal and low-lying areas.



The San Francisco airport is vulnerable to peak flooding of eight and a half feet (grey areas), which would overtop the existing levees. From Biging et. al (2012) forthcoming CEC report.

Contributors: Greg Biging, U.C. Berkeley; John Radke, U.C. Berkeley; Patrick Barnard, USGS; Peter Bromirski, SIO; Daniel Cayan, SIO; Steve Goldbeck, BCDC; Matthew Heberger, Pacific Institute; Noah Knowles, USGS; Jun Hak Lee, U.C. Berkeley.

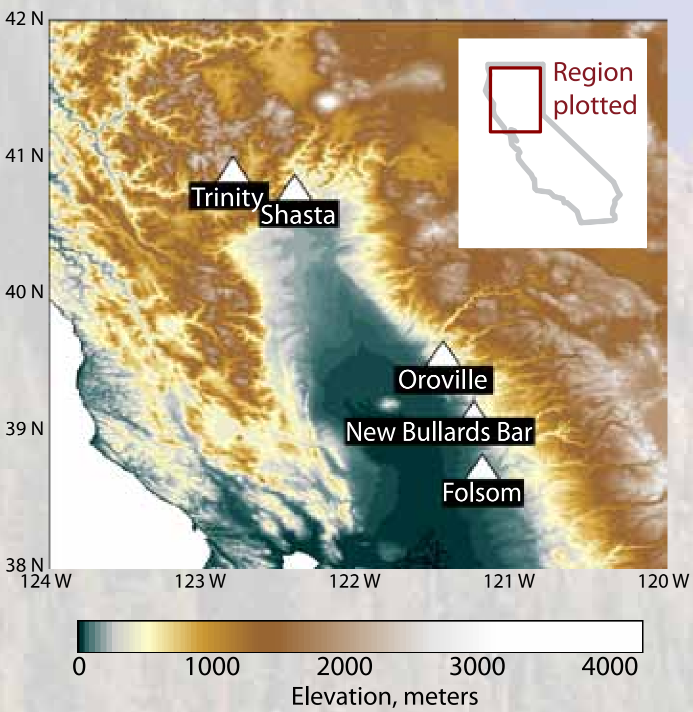
For more information: Biging, G., J. Radke, and J. H. Lee (2012): Vulnerability assessments of transportation infrastructure under potential inundation due to sea-level rise and extreme storm events in the San Francisco Bay Region. Paper for the California Vulnerability and Adaptation Study. Public Interest Energy Research Program. California Energy Commission report (forthcoming).

Reservoir Management

Konstantine P. Georgakos

"In the future, adaptive policy will help us better manage climate extremes."

Reservoirs are managed for a variety of conflicting objectives, such as environmental water flow, flood protection, hydropower, recreation, agriculture, and municipal water supply. Users want a steady and reliable water supply, but climate extremes and variability make this difficult. Right now, California's reservoirs are managed with fixed rules based on history. The INFORM project demonstrates that adaptive management policies, using the best available forecasts and modern decision science, can do better.



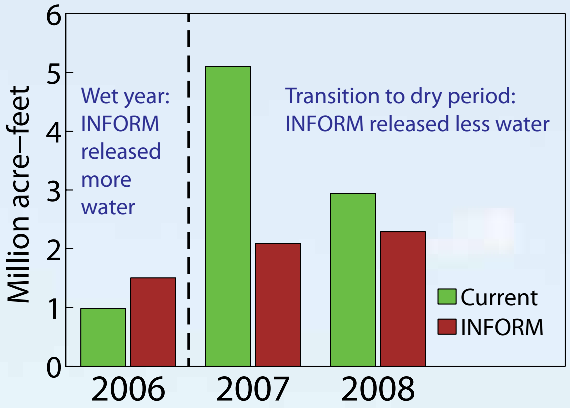
Northern California reservoirs that are part of the INFORM project, which uses real-time forecasts and decision science to better manage water resources. Adapted from Georgakakos et al. (2005) *EOS (Transactions of the American Geophysical Union)* v. 86 p. 122.

California's water system has a difficult job: dependably supplying water for hydropower, the environment, agriculture, and municipal water supplies while maintaining capacity to absorb potentially damaging floods. All this is done against a backdrop of variability ranging from a day's intense rainstorm to decades-long drought. These diverse and conflicting objectives can only be met through proper reservoir management.

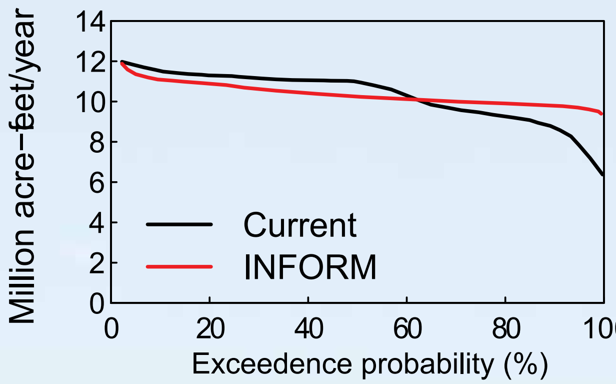
Currently, California's flood control operations are managed with fixed rules and observed-to-date precipitation and temperature; no forecasts are used. For water conservation only coarse predictions of above or below normal (wet/dry) years are used. This can contribute to large year-to-year fluctuations in the amount of water delivered. For example, in 2008 only about half as much water was delivered as in 2006. The INFORM project develops ways to use probabilistic forecasts and decision science to reduce the effects of climate variability and extreme events on the water system. The project is implemented in cooperation with national and regional weather forecasting and reservoir management agencies working in California.

Adaptive management is a key aspect of INFORM. Reservoir decisions are based on the best available forecasts and current data along with management objectives. Explicitly accounting for forecast uncertainty is another important factor that gives managers more confidence in using the results.

Both the weather/climate forecasts and reservoir decisions are made by a sophisticated series of models that cover time spans from six hours to many years. True to life, multiple (sometimes conflicting) management objectives are supported and the system's performance is continually evaluated.



During the test period, INFORM released more stored water from the reservoirs in wet periods and less in dry periods than current practice.



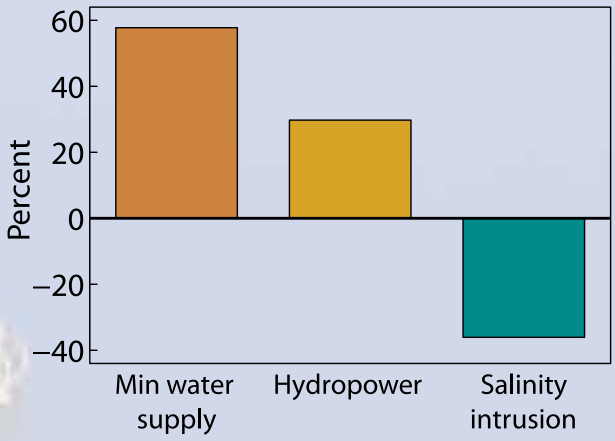
Using simulations of future climate, INFORM (red) maintains more uniform water deliveries year-to-year and higher deliveries in the driest years, compared to current methods (black).

During the current demonstration phase, INFORM output is being compared to the actual reservoir system and feedback is being collected from the forecast and management agencies. Real-time results are available to project partners through a secure web site.

Lessons Learned

In California, 2006 was wet, 2008 very dry, and 2007 a transitional year between the extremes. During this test period INFORM performed well, saving a bit more water than the old fixed rules during the dry year, yet releasing more water from storage during the wet year. And during the transitional year there were significant water savings.

The system can also be evaluated against future climates projected by climate models. Here, the difference between the fixed rules and adaptive management becomes even greater. INFORM gives a 58% increase in minimum annual water supply and 30% increase in reliable hydropower, yet reduces salt water intrusion into San Francisco Bay by 36%.



Compared to current practice, under future simulated climates INFORM gives a larger minimum water supply, more hydropower, and less salinity intrusion from the SF Bay.

Way Forward

Significant legal and institutional barriers must be overcome before the benefits of an adaptive management system such as INFORM can be realized. Key reservoir management organizations were established years ago when forecasts had appreciably less skill, yet such organizations can be hesitant to change from the old tried-and-true ways even now that forecasts have improved.

A feasible way to overcome these problems is if management organizations focus on laying out water policy objectives and methods to resolve conflicting priorities rather than specifying fixed reservoir operating rules. This would let operating rules evolve as science progresses, without requiring changes to the overall purpose of the rules or the way different objectives are balanced.

Lastly, adding groundwater and hydroeconomics to INFORM would extend its ability to allow managers to make the most productive use of California's water resources in the face of climate extremes and variability.

Contributors: Konstantine Georgakakos (Hydrologic Research Center, HRC); Aris Georgakakos (Georgia Tech); Nicholas Graham (HRC); Joseph O'Hagan (California Energy Commission); John Andrew (Department of Water Resources); Daniel Cayan (Scripps/UCSD).

For more information: Georgakakos, K. P., et al. (2012): Value of Adaptive Water Resources Management in Northern California under Climatic Variability and Change: Reservoir management. Journal of Hydrology, v. 412 p. 34-46.

http://www.hrc-lab.org/projects/dsp_projectSubPage.php?subpage=inform

Agricultural Impacts

Louise Jackson

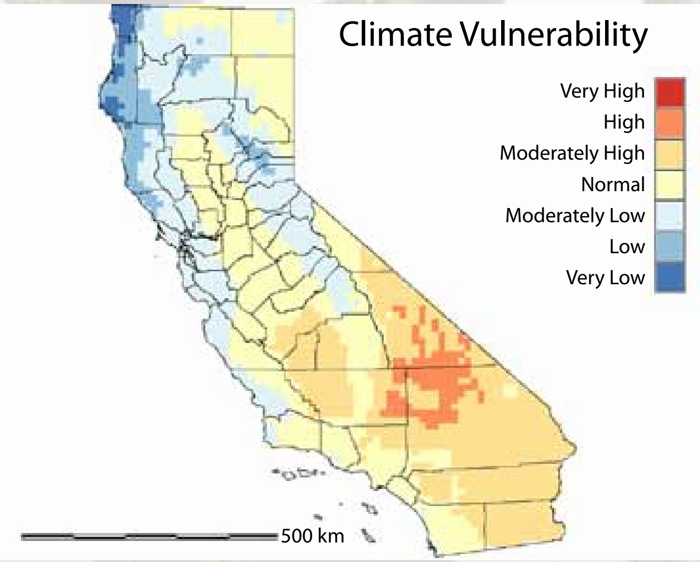
"The more diverse our crops are, the less chance they will be harmed by a single extreme event."

Agriculture is a key part of California's economy. Agricultural vulnerability to climate varies widely across the state, depending on factors such as how much water crops use and how variable local precipitation is. More diverse crops could increase resiliency to climate change and extreme events, but are costly to research and implement. Future water availability is farmers' top environmental concern, and could be addressed by strategic growth policies, more water efficient crops, or advanced irrigation technology.

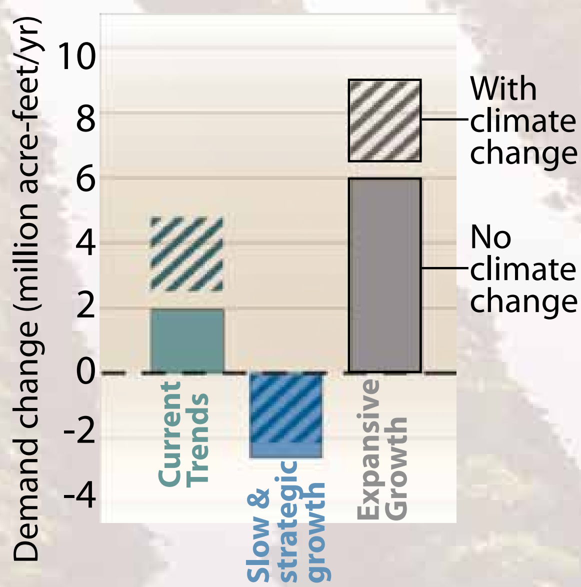
California agriculture is important not only to the state — generating $30B of income each year — but to the nation as well, having produced the highest agricultural crop value in the U.S. for over 50 consecutive years.

Climate change will alter chill hours (cold conditions needed for fruit and nut crops), heat waves, flooding, and other environmental factors affecting agriculture. Yet surveys suggest that farmers by and large are less concerned about these impacts than about indirect effects, such as regulations to curb climate change or higher fuel and energy prices that may result from climate change mitigation efforts.

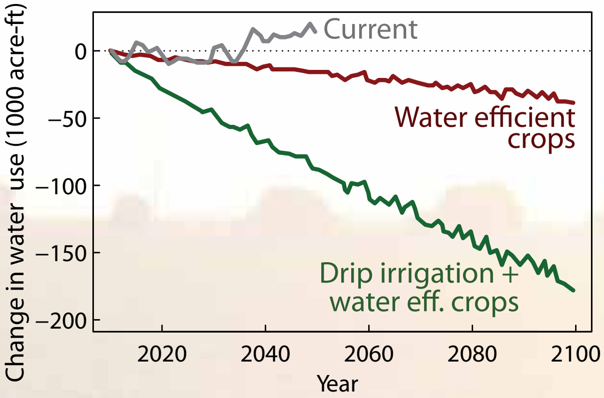
Of the environmental concerns farmers do list, lack of sufficient water is the main one. Research shows that there are ways to mitigate the effects of increasing aridity in California due to higher temperatures and the possibility of prolonged drought. For example, the change in water demand by 2050 is greatly influenced by California's overall growth and development policies. With slow and strategic growth, climate change does little to alter future water demand. Conversely, with expansive growth, climate change could have a large and accelerated effect on increases in water demand in both agricultural and other sectors.



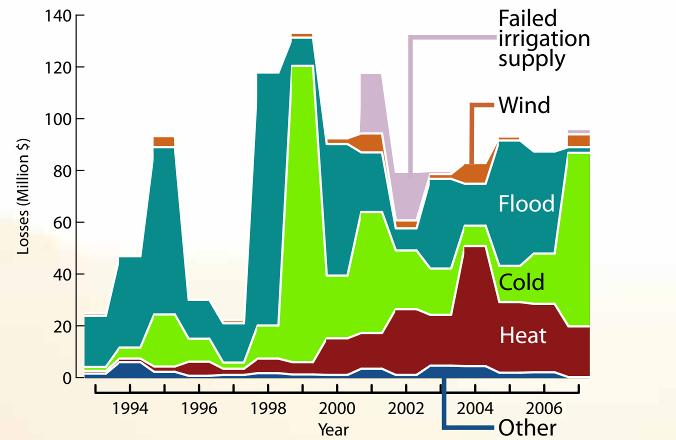
Not all regions are equally vulnerable to climate extremes and change. From an agricultural point of view, most of the vulnerability is determined by how much water a crop would lose to the air and how variable local precipitation is, though many other factors contribute. More diverse local crops can reduce climate vulnerabilities. Figure courtesy V. R. Hayden (UC Davis), from Jackson et al. (2012) forthcoming CEC report.



Estimates of how California's water demand will change by 2050 under different land use policies, either including (stripes) or neglecting (solid) climate change. Changes are relative to average of 80.1 million acre-feet. From *California water plan highlights Update 2009*, CA Dept. of Water Res.



Changes in Yolo County irrigation water demand over time for different scenarios of crops and irrigation technology. Drip irrigation (green) substantially reduces water requirements. V. Mehta, Stockholm Environmental Institute.



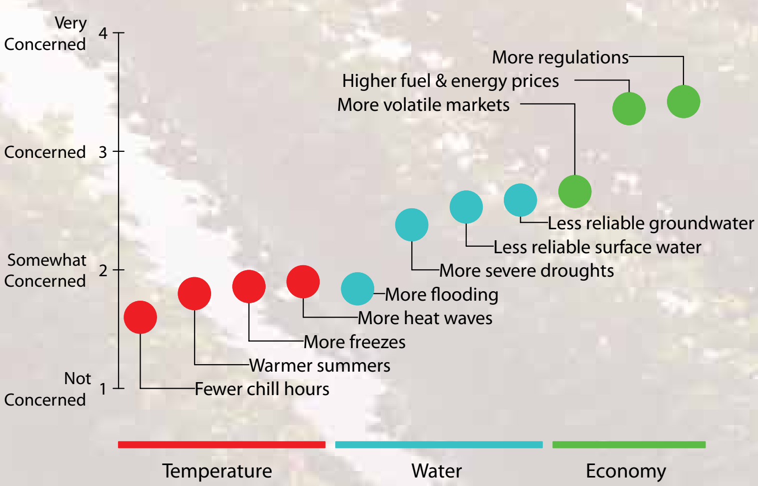
Insurance payouts for different kinds of agricultural losses in California. The biggest total payout was for flooding (blue), followed by freezes (green) and heat waves (red). Redrawn from Lobell et al. (2009), CEC report CEC-500-2009-040-F.

Other practical measures could be used to adapt to warmer conditions and potentially less water. More diverse and water efficient crops would have some effect. Adopting more efficient irrigation technology such as drip irrigation, which is already successfully used in other arid locations, would decrease water use, but reduce groundwater recharge too.

Greater regional crop diversity would make California more robust to extreme climate events, since freezes, heat waves, floods, and similar events often last only a week or so. A variety of crops with different environmental sensitivities and stages of growth would reduce the chance that an entire crop is harmed by a single extreme event.

Floods have generated the most insurance payouts for agricultural losses over the last 15 years, followed by freezes and heat waves. It is interesting to note that payouts for heat-related losses have been steadily increasing over that period. Flooding produces the largest covered losses, and flooding is projected to increase because of climate change, yet farmers in a Yolo County survey list increased flooding as one of their lowest concerns. This illustrates a disconnect between farmers and the research community that would be useful to address. Likewise, California has 3 million acres of crops with chilling requirements, and climate change is projected to steadily reduce the number of chill hours, yet farmers are less concerned about the reduction of chill hours than any other environmental change included in the poll.

Institutional support could help California agriculture become both more sustainable and more robust to climate extremes and long-term climate change. New and more diverse crops are insurance for future changes, but are costly to research and implement. A robust agricultural sector yields additional environmental benefits as well, since only 6% of California's greenhouse gases are produced by agriculture. Converting cropland to urban infrastructure increases greenhouse gas emissions and represents a loss of California's farming livelihoods.



Surveys show Yolo County farmers are relatively less concerned with the direct environmental effects of climate change compared to the indirect economic effects, such as possible regulations or implications for fuel prices. L. Jackson, UC Davis.

Contributors: Louise Jackson (UC Davis); David Lobell and Chris Field (Stanford University); Michael Hanemann (UC Berkeley); Richard Howitt (UC Davis); Amrith Gunasekara (CA Dept Food and Ag.).

For more information: Jackson, L., et al. (2009): Potential for adaptation to climate change in an agricultural landscape in the Central Valley of California. Report from the California Climate Change Center. CEC-500-2009-044-D. 170 pp. http://groups.ucanr.org/jacksonlab/files/66086.pdf

See also: http://viewer.zmags.com/publication/89b78978#/89b78978/4

Wildfire

Anthony Westerling

"The frequency of extreme fire seasons could increase more than 10-fold by the end of the century."

Wildfires cause deaths, destruction of property, and air pollution. Extreme fire years in California are often associated with clusters of lightning strikes that spark multiple ignitions. As the climate changes and summer becomes hotter and drier while the snow melts earlier, seasons with many large fires are likely to increase substantially, perhaps 10-fold or more. Thinning undergrowth is one strategy to reduce fire intensity and frequency. Building practices and the amount of development in wildlands also affect property losses from fire.

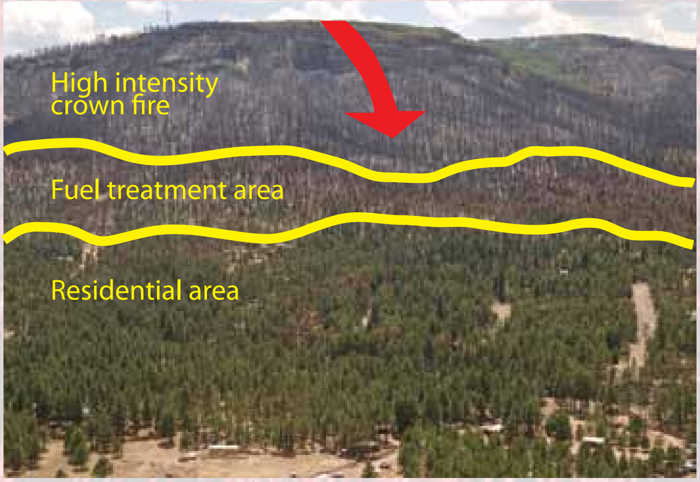
Climate describes a system with a set of possible outcomes. How we view an outcome depends on how we've placed our bets. In fire, most of our bets involve fuel management. In the Sierra Nevada fire suppression has excluded fires long enough that the vegetation has grown denser, leading to hotter burning fires that are problematic in a system not adapted to deal with the new fire intensity.

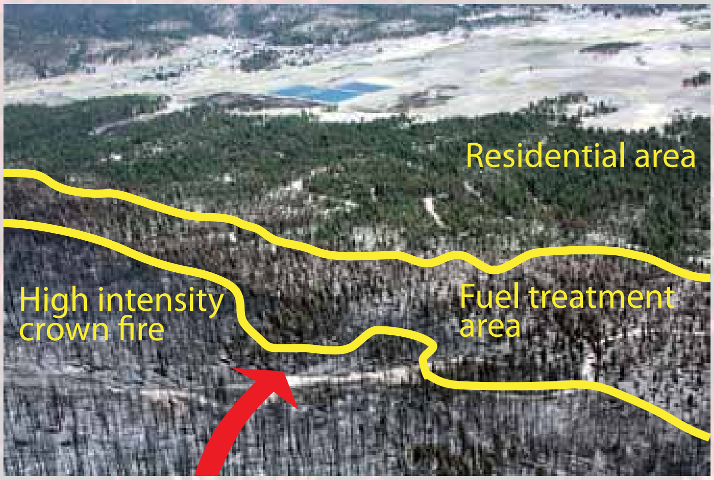
Although one tool is not appropriate for all ecosystems, thinning fuel on the ground can make some regions more resilient to fire. For example, the Rodeo-Chediski fire in 2002 burned though some places that had been thinned and others that hadn't. The thinned areas had living trees standing after the fire, while in the untreated areas all the trees were killed. However forests that are naturally dense and moist should probably not be thinned as it might make them less resilient to a fire, not more.

Another way we hedge our bets is where and how we build. Development in forested regions carries greater fire risks. Some suburbs encroach into wildland that easily supports wildfires. Building techniques such as unscreened ventilation holes in eaves allow ash and embers to enter, which can burn down the house even after fire crews leave the area.

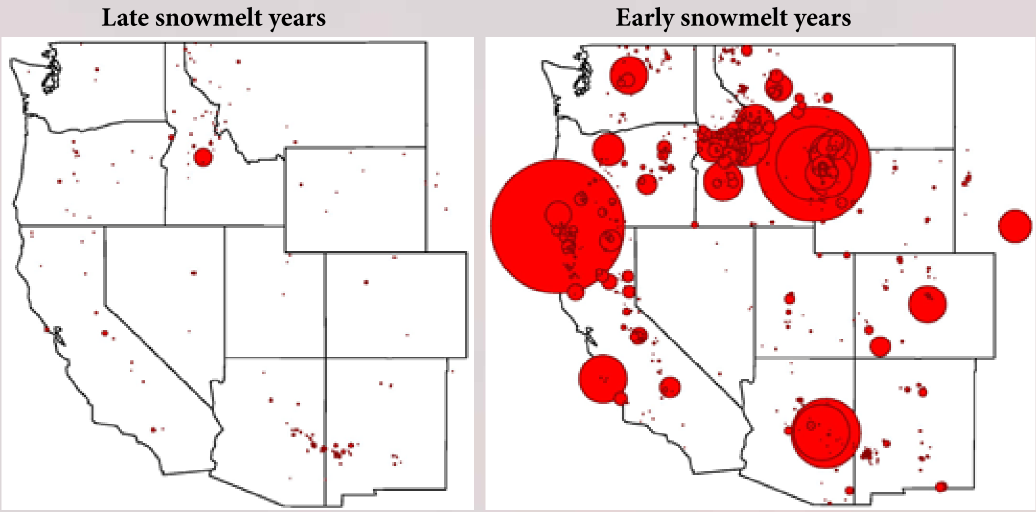
Year-to-year variability in fire seasons is greatly influenced by clusters of lightning strikes. For example, in 2008 the state experienced many fires started by lightning. The fires weren't that big, but there were a lot of them. Clustered lightning strikes have given us some of the biggest fire years in the Sierra Nevada in recent decades.

Summer temperatures do not always influence fire, especially in locations that are already hot and dry to begin with. For example, grass and shrub fires are not directly related





Fuel treatment helped save the town of Alpine, AZ from an intense, fast-moving crown fire in 2011. Black areas show near-complete burning; brown areas are fire singed; green areas are largely unburned. Redrawn from "How fuel treatments saved homes from the 2011 Wallow Fire," from the Wildland Fire Lessons Learned Center (wildfirelessons.net). Left photo: US Forest Service/Kari Greer. Right photo: US Forest Service/Tim Sexton, District Ranger - LaCroix Ranger District.



Each dot shows a large forest fire (at least 1000 acres) that occurred over the last few decades on federal forest land. Dot size is proportional to the fire size. All large forest fires in CA in recent decades have occurred in years with an early snowmelt. Such years will increase in coming decades.

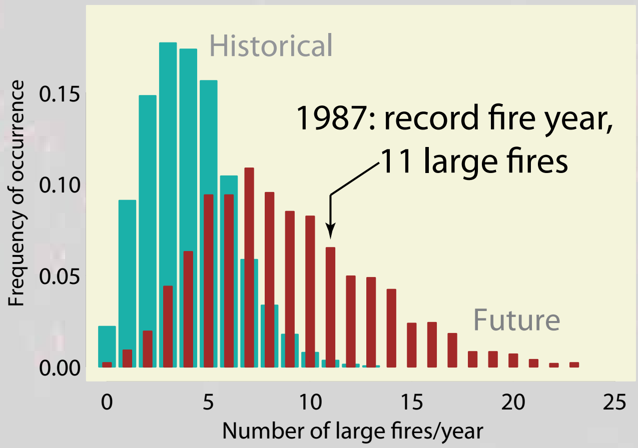
to temperature, but rather to the existing fuel load, which is driven by such factors as last winter's precipitation and the time since the last fire. On the other hand, fires in forests are strongly affected by spring and summer temperatures. There is also a greatly enhanced chance of big fires in years the snow melts early. All large forest fires in California in recent decades have occurred after an early snowmelt. Such years are very likely to become more common in coming decades.

The worst recent fire season in the Southern Sierra Nevada was 1987, with 11 large fires. Under moderate warming scenarios, the chance of a year with 11 large fires increases more than 10-fold by the end of this century. Under drier but still plausible scenarios, the frequency increases 40 times. If fires become this frequent the vegetation will likely shift to an entirely different fire regime (such as forests being replaced by scrubland), but this illustrates how sensitive extreme fire seasons are to climate warming.

The size of fires that occur is also important. Total acres burned will likely increase by up to 300% in Northern California, the Sierra Nevada, and the coastal ranges. In Southern California, fire size is driven by Santa Ana winds. The top 1% of fires will likely increase about 40% in size by end of this century. To get back to historical fire sizes, Santa Ana winds would have to drop in frequency by about 45%.

Fires release stored carbon dioxide and generate air pollution through soot and smoke. The pattern of increased pollution will follow the pattern of increased acreage burned. Much of the particulate emissions will be concentrated in the late summer in the Central Valley, which has health implications for the residents.

Ultimately, how much people are affected by changes in wildfires will be greatly influenced by population growth and urban sprawl. If development continues into the wildland, then more people and property will be put at risk as the frequency and size of fires increases in coming decades.



1987 was a record fire year for the Southern Sierra, with 11 large fires. Simulations of future climate (red) show the frequency of such years is likely to increase greatly by the end of the century.

Contributors: Anthony Westerling (UC Merced), Benjamin P. Bryant (Pardee RAND Graduate School), Timothy J. Brown (Desert Research Institute), Crystal Kolden (U. of Idaho), John T. Abatzoglou (U. of Idaho), Max Moritz (UC Berkeley), Meg A. Krawchuck (UC Berkeley), Enric B. Presas (UC Berkeley), John J. Battles (UC Berkeley).

For more information: Westerling, A. L., B. P. Bryant, H. K. Preisler, T.P. Holmes, H. G. Hidalgo, T. Das, and S.R. Shrestha (2009): Climate Change, Growth and California Wildfire. Public Interest Energy Research, California Energy Commission Report CEC-500-2009-046-F, Sacramento, CA.

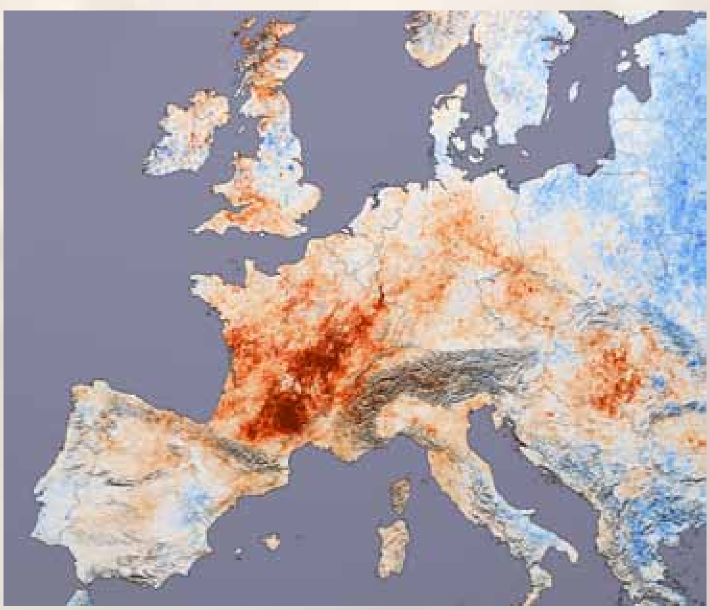
Human Health

Bart Ostro

“It’s not just about melting glaciers. There will be significant public health impacts in our state.”

Heat waves kill people, primarily through cardiovascular diseases, which carry a 5% greater risk of mortality for a 10°F increase in daily temperatures. Hot days also favor forming ozone, which is associated with asthma attacks, sick days, visits to the emergency room, and premature death. The 2006 California heat wave killed about 400-650 people and generated about $5.4B in damages. As the climate warms heat waves will become longer, more frequent, and accompanied by hot and humid nights, which are particularly hard on people. Based on current projections, by 2050 about 10,000 California residents could die of heat-related causes every year if no preventive measures are implemented.

Climate extremes such as heat waves, floods, and fires harm people’s health in many ways. There are direct effects such as cardiac failure due to the heat; indirect effects such as more ozone forming on warm days; and social and economic disruption, for example from emergency room visits or sick days. Two effects are particularly well documented: the direct effect of higher temperatures on the body and the indirect effect of ozone.

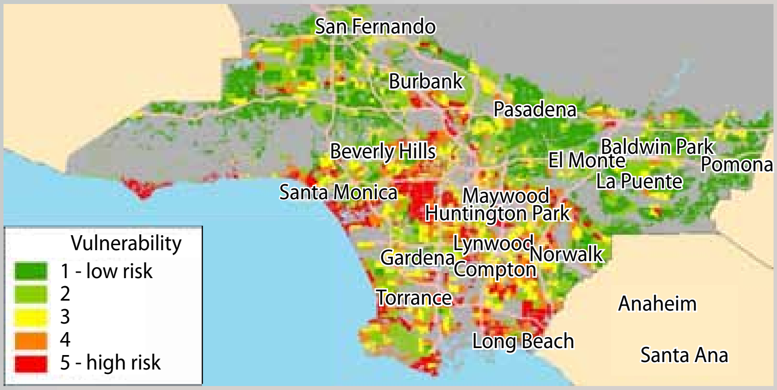


About 30,000 people died from the 2003 European heat wave. Colors show satellite-based measurements of unusually warm temperatures during the event. Dark red areas are up to 18°F warmer than usual. Image courtesy Reto Stockli and Robert Simmon, based upon data provided by the NASA MODIS Land Science Team.

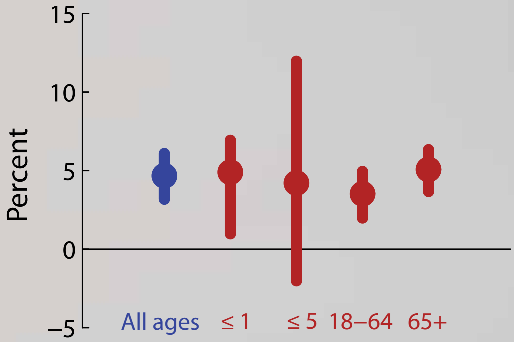
High temperatures and heat waves kill people primarily through diseases of the cardiovascular system, such as heart attacks and stroke. On average, a 10°F increase in daily temperature gives about a 5% increase in the risk of dying from cardiovascular disease. Heat waves give even greater risks, which increase with the heat wave’s duration and intensity. Heat waves are projected to become longer and more frequent in the future. The risks are higher when nights are hot and humid, which give less chance for people to cool off and recover from the day’s temperatures. These warm, humid night heat waves are expected to increase.

The 2003 European heat wave resulted in about 30,000 deaths. Closer to home, the impact of the 2006 California heat wave can be estimated by statistical techniques developed for air pollution studies, which are able to take into account other influences such as age or pre-existing conditions. About 400-650 people died as a result of the 2006 heat wave, with $5.4B in associated damages.

Where someone lives makes a difference to how susceptible they are to a heat wave. Cities have a heat island effect, with higher temperatures in the paved inner core. In California, there are more dark, heat-absorbing surfaces and fewer trees in lower income areas, which puts the residents at a higher risk from extreme temperatures. Also, death and hospitalization rates due to heat waves are higher along the coast, presumably because people are less used to the heat there.



Vulnerability of people in Los Angeles to climate change, including factors such as heat, elevation, and income. From P. English et al. (2011), *A screening tool for climate change population vulnerability assessments*, CA Dept. of Public Heath.



Excess risk of death (and 95% confidence interval) from a 10°F increase in temperature, by age range. Although seniors are especially affected by heat, all age groups have elevated risks.

A common misperception is that people who die during heat waves are near death anyway. Studies show that most people who die of heat related deaths were not near death to begin with, and could have lived considerably longer. Likewise, although the effect is highest on the elderly, all age groups are affected. While the overall increase in mortality for 10°F of warming is 5%, for those aged 18-64 it is 3.5%.

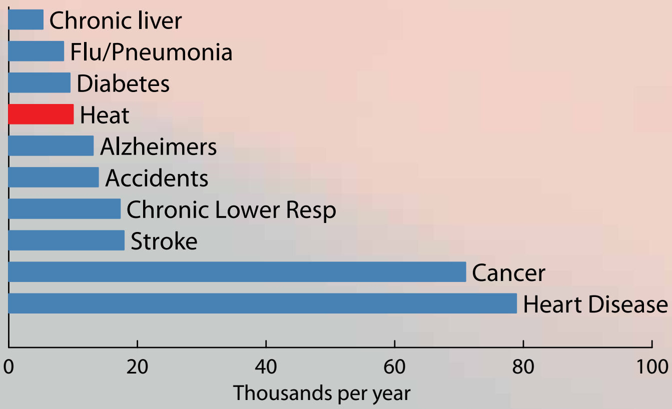
Death is not the only public health impact of high temperatures. There are more emergency room and hospital visits, and cases of dehydration and intestinal infections in children 5-18 increase as well. The latter may be because unrefrigerated food spoils faster on warm days.

There is more ozone generated on hot days, and many parts of California are already above state and federal ozone standards. Ozone is associated with premature death, emergency room visits, asthma attacks, and sick days. Studies of ozone and public health in Los Angeles and the San Joaquin valley suggest there will be about a 25% increase in the number of high ozone days by 2050, and 200 extra ozone-related deaths per year with a cost of $0.8-3 billion. These impacts are likely to be disproportionally on lower income groups.

Future trends

Assuming current emission rates of greenhouse gases, if no preventative measures are taken then by 2025 there are likely to be 4,300 deaths per year in California due to heat, and 10,000 per year by 2050. This would make deaths from heat greater than from the flu and pneumonia or diabetes, and nearly as high as from accidents.

There will be other health impacts as well, such as from more wildfire smoke (which irritates the respiratory system and worsens chronic heart and lung diseases), and from infectious diseases that transmit through mosquitoes or rodents that thrive in warmer conditions. Overall, climate change and extremes will have a significant impact on the health and well-being of California's residents.



Projected California death rates by the 2050s if no preventative measures are taken, and assuming current rates of disease and climate change.

Contributors: Bart Ostro, (California Office of Environmental Health Hazard Assessment) Rupa Basu, (California Office of Environmental Health Hazard Assessment) and Paul English (California Department of Public Health).

For more information: Ostro, B., et al. (2009): Estimating the mortality effect of the July 2006 California heat wave. CEC report CEC-500-2009-036-D.

Basu, R., and Ostro, B. (2009): A multi-county analysis identifying the vulnerable populations for mortality associated with high ambient temperature in California. CEC report CEC-500-2009-035-F.

Background image courtesy U.S. National Institutes of Health image bank .

Plants and Animals

Terry Root

"We're going to get lots of surprises—and lots of extinctions."

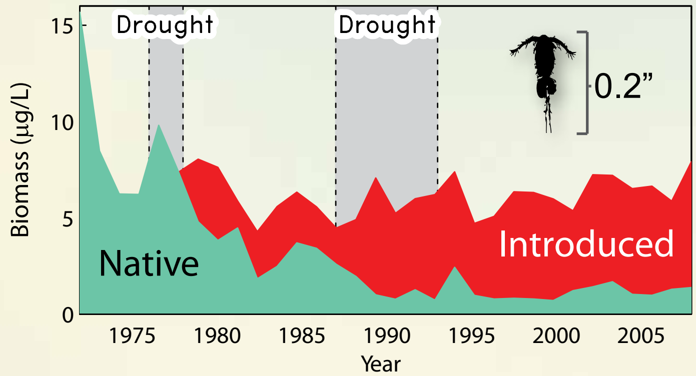
Interactions between different species in an ecosystem are complex, and climate extremes and change will affect plants and animals in ways we might not expect. Ecosystems are generally moving northward and to higher elevation, but at different rates and not necessarily in quite the same direction. The changing relationships between interconnected species will provide additional stresses on plants and animals that in many cases are already struggling. Droughts can cause saltwater intrusion in estuaries, floods can deposit silt on fish eggs, and heat waves can kill bird eggs and chicks. Fires are beneficial to some species, but ones that occur too often can be harmful.

As the climate changes, species' ranges will move in different directions at different rates, leading to unexpected changes in populations as interactions among species are disrupted. Climate extremes represent an additional short-term stress in addition to these slower changes.

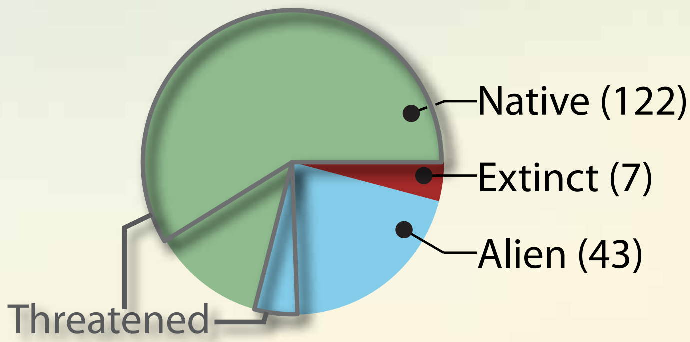
California has tremendously diverse wildlife, with its varied regional climates from the arid inland desert to the cold meadows of the high Sierra Nevada, from the mild and dry southern coastal Mediterranean areas to the damp and heavily forested Northern coasts. Climate change already affects our state's wildlife; for example, at the turn of the last century, the American Pika (a small mammal adapted to cold mountain regions) lived up to 7,800' elevation in the Sierra Nevada. By 2004, with warming temperatures, they had moved as high as 9,500'. Many more species will likely move Northward or to higher elevations as the climate warms.

Climate change affects plants and animals in ways we don't fully understand, and a change in one species has cascading effects on others. As a result, the overall changes in ecosystems can be surprising. For instance, wolves were nearly eradicated from parts of the western U.S. in the 1870s, but this had the (at the time, unexpected) result that coyote populations boomed. In response, the coyote population was reduced, but this greatly increased the red fox population. Different species are intertwined in sometimes unexpected ways.

Darwin thought entire communities were so interconnected that they would move together under environmental pressures. However, this is not happening in California. Instead, different species are moving to different areas at different rates, which alters or breaks down interactions among species. This can be critical in, for example, predator-prey relationships, or between plant-eating species and the host plants they depend on. In the end, we don't know how all these changes will proceed, but they are likely to stress many species. Some will go extinct as a result.



During periods of drought (grey boxes), native zooplankton in San Francisco Bay estuary regions declined, to be replaced by introduced species. Redrawn from Winder et al. (2011), *Ecology Letters* v. 14 p. 749.



Although California inland fishes are dominated by native species, the majority are critically or highly vulnerable (grey outline). Alien species are relatively less threatened. Redrawn from Moyle et al. (2011), *Biol. Conservation* v. 144 p. 2414.

Effects of Climate Extremes

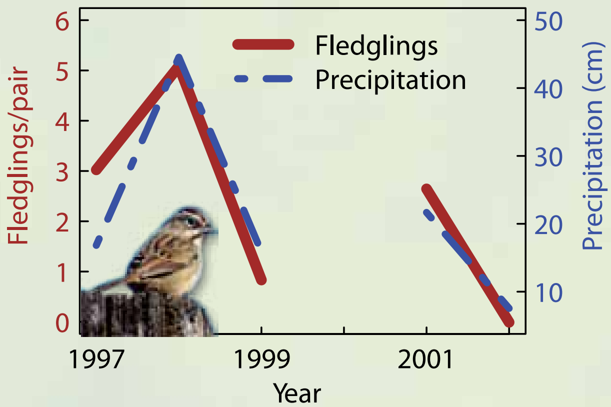
Droughts deplete rivers, allowing more saltwater intrusion into estuaries. Non-native species can then move in. For example, fresh water from the Sacramento and San Joaquin rivers transitions to salt water in the San Francisco Bay between Vallejo and Antioch. During the 1987 to 1995 drought alien zooplankton species infiltrated the area, and the total mass of native species dropped sharply.

Native fish, especially salmon, are valuable for fisheries but are greatly affected when floods deposit silt on their eggs. Many species of native fish are in decline for reasons such as dams and environmental degradation; climate extremes and long-term change are yet more pressure.

Some species have adapted to California's wildfires, and need fire to complete their growth cycle. For example, the seeds of Mazanitas and California lilacs must go through fire before they germinate. More frequent fires in the future might be guessed to have beneficial effects on such species, but this is not always the case. If fires become so frequent that the juvenile plants do not have time to produce seeds before the next fire comes along, abundance could decline.

Extreme heat waves can be a problem as well. The heat wave of May 15-16, 2008 caused extensive breeding failure of Cormorant seabirds on the Farallon Islands, about 27 miles west of the Golden Gate bridge. Nests were abandoned in the scorching weather, and the eggs and chicks died. Some parents stayed behind to shade their nests and were killed as well. Heat also degrades the quality of grapes used in California's economically important wine industry. Hotter conditions means the grapes must be picked early, when sugar content is high, which hurts the quality of the grapes.

Healthy ecosystems are the foundation of much of California's economy and quality of life. Climate change is underway, and climate extremes are already happening. Unable to adapt through technology, wildlife bears the brunt of these changes. We can get some understanding of the outcomes by studying the past, but should be prepared for surprises.



The number of fledglings (chicks) per pair of Rufous-Crowned Sparrows in S. California depends on precipitation, an illustration of how wildlife is affected by climate extremes such as droughts. Redrawn from Bolger et al. (2005), *Oecologia* v. 142 p. 398. Image (CC) Maggie Smith, slomaggie@flickr.com.

Contributors: Terry Root (Stanford University); David Ackerly (UC Berkeley); Ellie Cohen (PRBO Conservation Science); Steve Davis (Pepperdine); Healy Hamilton (UC Berkeley); Rebecca Hernandez (Stanford); Jonathan Levine (UC Santa Barbara); Max Moritz (UC Berkeley); Peter Moyle (UC Davis); Amber Pairis (CA Dept of Fish and Game); Sarah Pittiglio (CA Energy Commission); Phil Rundel (UC Los Angeles); Erica Zavalata (UC Santa Cruz).

For more information: Winder, M., AD Jassby, and R. MacNally (2011). *Ecological Let.* 14 (8): 749-757.

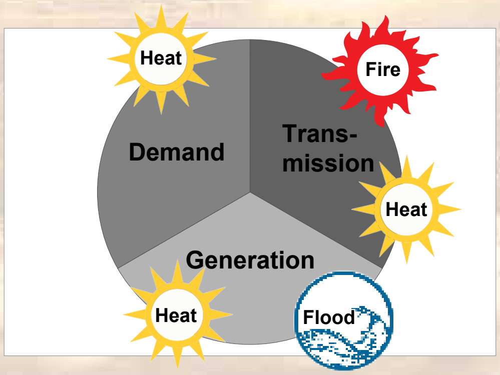
http://www.energy.ca.gov/2009publications/CEC-500-2009-025/CEC-500-2009-025-F.PDF

Energy

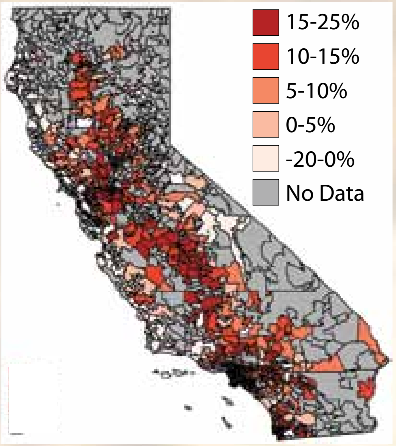
Maximilian Auffhammer

"Fires, heat, and floods are going to put additional pressure on California's energy system."

Climate extremes affect energy demand (heat waves drive peak power use), transmission (fires and high temperatures affect power lines), and generation (sea level rise will likely affect some coastal plants, and power plants become less efficient at high temperatures). As the climate gets warmer year-round, more people are likely to install air conditioners, which means that the extra increment of energy demand experienced on the hottest days of the year is likely to grow by about 20%. Population increases have the biggest effect on total energy demand, but climate change and heat extremes have a great influence on demand during the few critical peak demand days of the year.



Different climate extremes can affect the electrical system. Heat affects demand; fire and heat affect transmission lines; and temperatures and potential flooding of coastal locations affect power plants and substations.



By the end of the century, warmer temperatures could notably increase household electricity consumption in California. Redrawn from Auffhammer and Aroonruengsawat (2012), forthcoming CEC report.

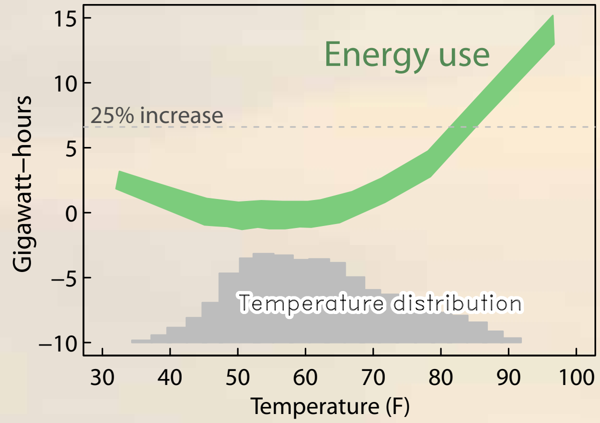
Energy demand, generation, and transmission in California are all affected by extreme climate events such as wildfires, heat waves, and floods.

The biggest effect is going to be higher electricity demand. Heat waves drive peak demand, which is critical because the entire energy system is built to handle peak demand days. As the climate gets progressively warmer, extreme heat waves will reach temperatures we have not experienced before. Peak demand is a function of temperature; for example, average electrical demand on an 80°F day is 25% higher than on a 60°F day. At warmer temperatures, the proportional increase in demand goes up even faster.

Besides heat waves, average summer temperatures have an effect as well. As temperatures get warmer, more people will buy air conditioners, especially along the densely populated coast. Newly built houses will be more likely to include air conditioning from the start. This means that the increase in electrical demand on hot days will become even greater than it is today, likely by about 20% based on historical patterns of air conditioning use and electrical demand. Warmer temperatures affect industry as well as residential electricity use since many manufacturing processes require cooling. Non-climate factors such as household income are important to energy demand too, with higher income households showing a bigger increase in electrical demand on hot days.

By the end of the century, and holding population, appliance efficiency, and income constant, we could get a significant increase in residential energy consumption given the current

Some power transmission lines in California (lines) will be 25-45% more likely to be affected by a wildfire due to the changing climate by the end of this century. From Sathaye et al. (2011), CEC publication CEC-500-2011-XXX.



Energy demand in California (green) depends on the temperature, with demand rising sharply as temperatures go above about 80°F.

rate of climate warming. The demand on many summer days could exceed the 90th percentile of today's demand; i.e., by the end of this century, a substantial portion of the summer could exceed the 10 highest demand days today.

Warm days have effects on energy infrastructure in addition to increasing demand. Power plants and transmission lines become less efficient as temperatures go up. Although these effects are not large – right now transmission losses are about 4% on the warmest days – they reduce the efficiency of California's energy infrastructure the most on the days it is most stressed.

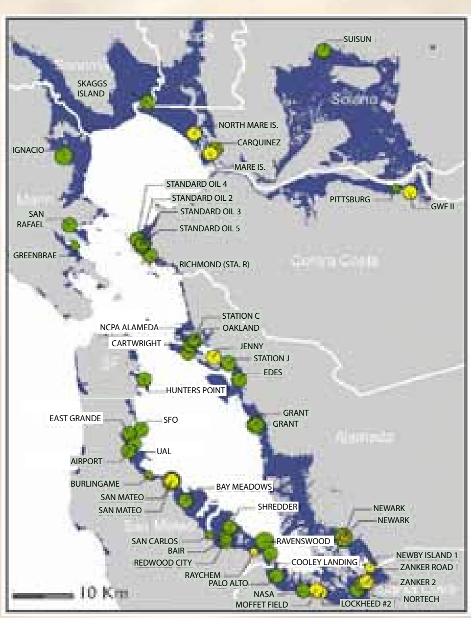
Wildfires and Sea Level Rise

Wildfires can have a significant impact on transmission lines, either directly or by depositing ash and soot on the line. There is a tremendous intersection between areas of high fire risk and where these lines currently run or are planned to be built. Under plausible future climate scenarios, by the end of the century the chances that a line will be affected by a fire go up by 25-45% in some parts of the state.

Sea level rise could potentially put coastal power plants and substations at risk. The danger comes from gradual sea level rise due to the warming climate combined with a climate extreme, such as a big storm surge with high waves. As the climate continues to change, we will have to think about where new energy infrastructure should be located and how to protect current infrastructure near the coast.

Finally, it should be kept in mind that population increases will have a bigger effect on California's energy demand than climate change, and how much and where the population will go up is uncertain. Nevertheless, climate change and extremes will have a significant effect on the state's energy demand, particularly on the few critical peak demand days of the year.

San Francisco Bay area electrical substations that will potentially be at risk by the end of this century from rising sea levels combined with high water levels due to storm surges and waves. From Sathaye et al. (2011), CEC publication CEC-500-2011-XXX.



Contributors: Maximilian Auffhammer (UC Berkeley); Jayant Sathaye (LBNL); Larry Dale (LBNL); Joshua Viers (UC Davis); Sebastian Vicuna (U of Chile); Guido Franco (California Energy Commission).

For more information: Sathaye et al. (2011): Estimating risk to California Energy Infrastructure from projected climate change, CEC publication CEC-500-2011-XXX. http://www.osti.gov/bridge/servlets/purl/1026811/1026811.PDF

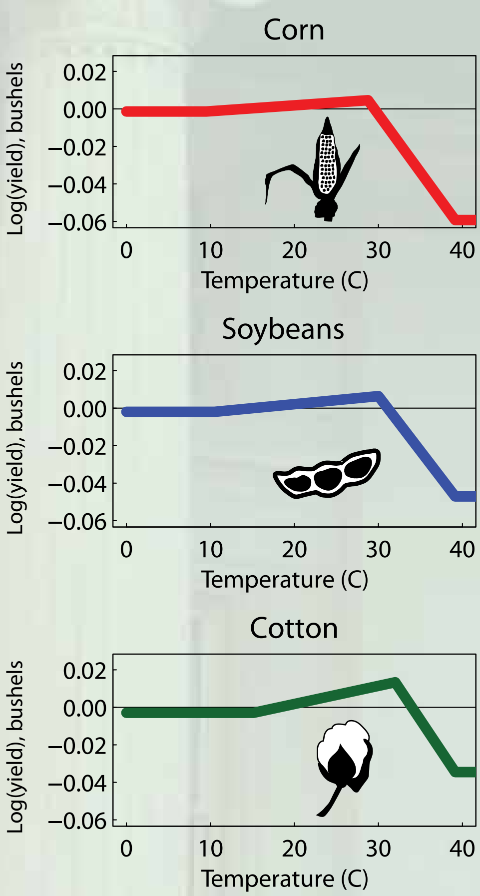
Auffhammer, M., and A. Aroonruengsawat (2011): http://www.springerlink.com/content/77n789r56084553j/

Economics

Michael Hanemann

"Economic losses from extreme events can increase greatly once a threshold is crossed."

Extreme climate events will probably dominate total economic losses from an altered climate. For many extremes there is a threshold effect, with mild losses for moderately sized climate swings but a sharp transition to major losses for larger climate swings. These thresholds have not always been taken into account when estimating the economic impact of climate change. Likewise, global estimates of temperature changes hide the fact that warming in a region can be much greater. When thresholds are taken into account, extreme events dominate economic losses. Some physical systems behave similarly. For example, the yield for some crops increases slowly as the climate warms until a threshold is passed, after which yield declines rapidly.



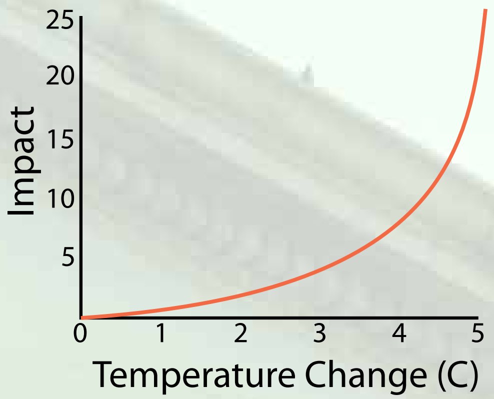
Yields from these economically important crops initially increase when temperature goes up, but then drop sharply at higher values. Redrawn from Schlenker and Roberts (2009) *Proc. Nat. Acad. Sci.* v. 106 p. 15594.

Reducing greenhouse gas emissions to the atmosphere requires global coordination. Yet the impacts of climate change and how to adapt to them are essentially exercises in local risk management. Tools for this problem have been developed and are used in finance and economics, but have not yet been fully applied to changing climate extremes.

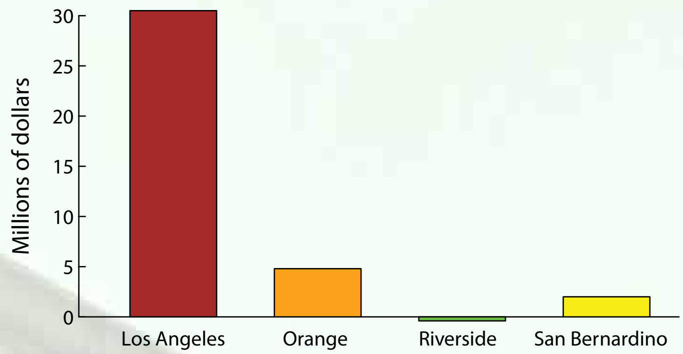
From an economics point of view, an extreme event is a combination of an exceptional weather or climate event (such as a flood or drought) with unusually severe consequences (such as massive crop failure). The consequences of an extreme event generally increase more than proportionally to the magnitude of the extreme. For example, a drought that lasts twice as long might give six times the economic damages.

In many cases the economic losses can be small until a threshold is crossed, at which point they increase rapidly. Flood waters cause little damage until a levee is overtopped; a drought has little impact until water rationing kicks in; a heat wave can become hot enough to destroy a crop; or a disruption to a business may last long enough to trigger layoffs.

Previously, much of the economic analysis of losses from climate change has not taken thresholds into account. Indeed, there has been only a slow appreciation that the average view given by global climate models does not describe local impacts. One widely used global climate model gives an average global temperature increase of about 2 C. Yet the warming over the western U.S. is 3.3 C, the warming in California's summer is 4.6 C, and in the central valley it is close to 5 C.



Schematic illustration of how some impacts from climate change can increase sharply once the global mean temperature increase passes a threshold, such as 4 C.



Damage to beaches and the local economy from a single stormy winter, such as 1982-83, can be extensive and fall unequally on beach users and businesses in different counties.

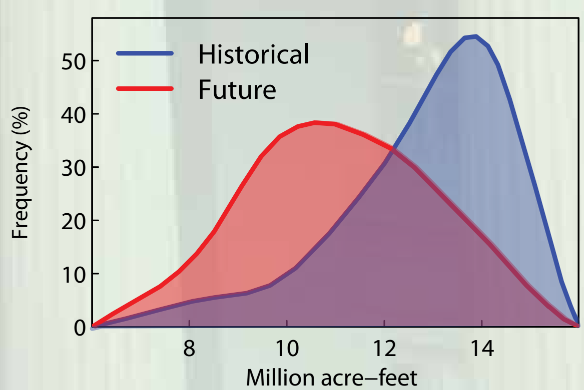
Because losses increase greatly beyond thresholds, there is a huge difference in economic impacts between a warming of 2 C and 5 C. Total losses are dominated by a few extreme events that are not seen in bland global averages.

Downside risk

People place extra value on avoiding negative consequences (downside risk) compared to gaining positive consequences. For example, a water supply manager would place little value in delivering 10% more water to customers than needed, but find considerable negative consequences to delivering 10% less than needed. People are willing to pay a premium to avoid the downside risk. Up to now, many economic analyses of climate losses have not taken this into account, and so do not show the true costs of climate extremes and change.

Physical systems can have this asymmetry as well. For example, some crops do better under warmer conditions, but if it gets too warm then yields decline sharply. Some analyses have assumed that the gains are about equal to the losses, with little net effect. More careful research shows that for many crops the gains under warming are modest and incremental until a threshold is passed, at which point the losses accumulate far more rapidly.

Economic analysis comes at the end of the climate analysis process, which starts with global population projections, calculates greenhouse gas emissions and their effect on the climate, estimates changes in physical variables, and then finally gets to economic impacts. But the economic impacts are arguably the most relevant to people's lives. Fundamentally, adapting to climate change and a shift in climate extremes is a process of altering the threshold above which severe economic losses are incurred, and reducing the additional increase in damages once any threshold is passed.



One model estimate of future water deliveries in the Central Valley shows a shift towards lower average yearly deliveries by the end of this century (red), even though the minimum and maximum values are maintained. From Hanemann et al. (2009) "The Downside Risk of Climate Change" presented at the European Assoc. Environ. and Res. Econ. Ann. Meeting.

Contributors: Michael Hanemann (Ariz. State Univ., UC Berkeley), Max Auffhammer (UC Berkeley), Richard Howitt (UC Davis), Wolfram Schlenker (Columbia, UC Berkeley), Charles Kolstad (UC Santa Barbara), Alan Sanstad (LBNL).

For more information:

Hanemann, M., et al. (2006): The economic cost of climate change impacts on California water: A scenario analysis. CEC report CEC-500-2006-003.

Available at: http://www.energy.ca.gov/pier/project_reports/CEC-500-2006-003.html

Barriers to Adaptation

Susanne Moser

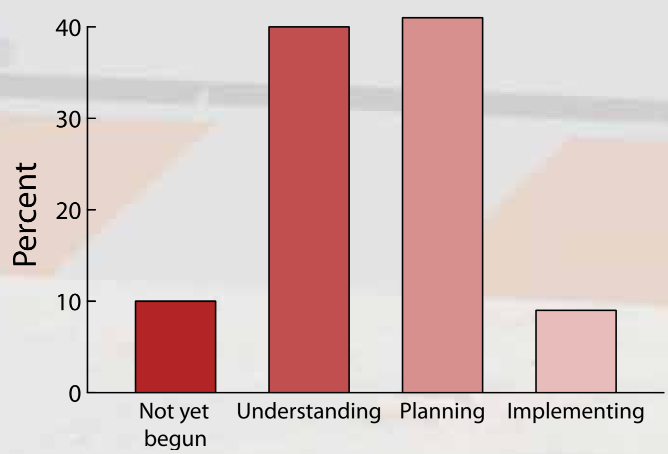
"Climate extremes are a magnifying glass for the vulnerabilities we already face."

Although communities show a growing interest in adapting to climate extremes and change, most are still in the early stages. Lack of technical solutions is generally not the issue. The biggest barriers to implementing adaptation plans are institutional, motivational, and economic. Planning for climate change requires doing something new and different. Lack of time, staff, and technical expertise are also problems. Local leadership is key to overcoming these barriers, which are often local in origin. Belief that the region is vulnerable to extremes is also motivational. In practice, integrating adaptation strategies into the regular community or coastal planning process is a common way to begin addressing the issue.

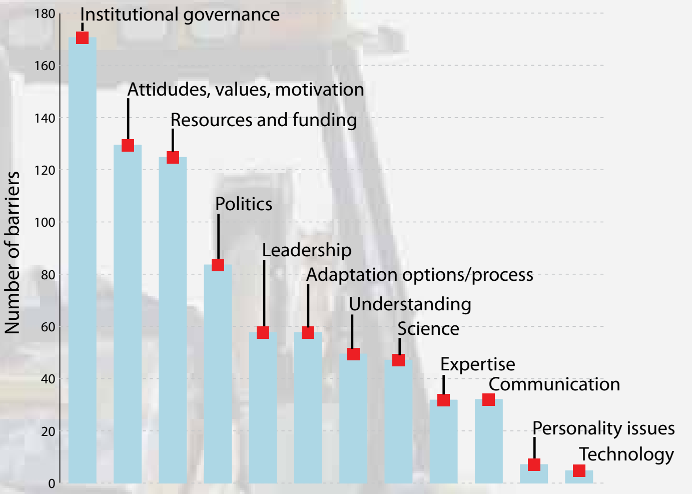
Weather and climate extremes harm California's economy, people, and infrastructure. The damage from an event depends on what is in harm's way ("exposure") and the sensitivity to the extreme event. If exposure is significant and sensitivity is high, even a modest climate extreme can create a dangerous situation. Climate adaptation aims to reduce vulnerability by decreasing exposure, reducing sensitivity to extremes, and increasing response capacity. The ultimate adaptation option is reducing greenhouse gas emissions globally, but adapting to the local effects of climate change and extremes will be needed in any event.

Adaptation may include technical measures such as building a seawall, moving infrastructure to higher ground, or implementing drip irrigation. However, broad institutional, political, and community support is needed to make technical approaches viable, and the biggest barriers to adaptation often lie in these other areas. Policy or planning tools for adaptation might involve land use policies, building codes, or water rights. Financial mechanisms needed to support adaptation include insurance pools, redevelopment funds, and water trading schemes. Behavioral approaches include education, disaster preparedness, and decision support systems. Without this support, technical approaches alone are unlikely to be successful.

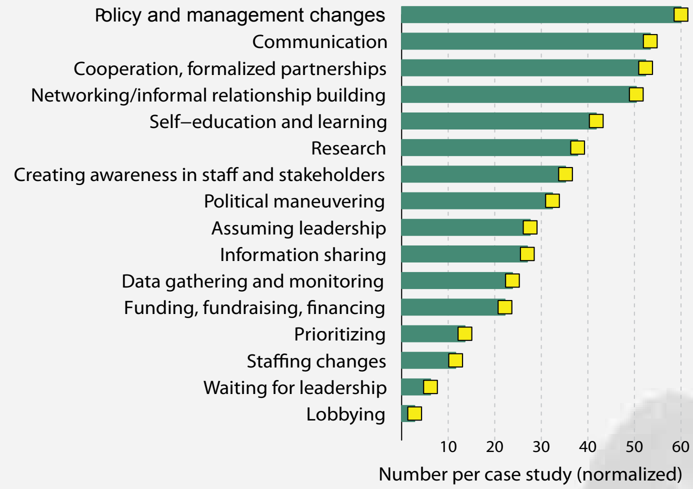
The way these factors interact is illustrated by the levees that prevent flooding around the San Francisco airport. Rising sea level will put the airport at risk of more frequent flooding as the century progresses. A technical approach is to raise the levees. However if the levees are expanded into the airport property, the runways would be shortened, impeding flight operations. Expanding the levees into the bay is currently prevented by policies that protect the bay from being filled. So a technical solution to the problem (a higher levee) requires policy changes first. These additional barriers to adaptation can involve considerable expense and time above and beyond what expanding a levee would cost, making the project nearly unattainable with current financing plans. Public and political support is then needed, which further requires public outreach and stakeholder involvement to advance such plans.



Status of California coastal communities in the climate adaptation process, as of Fall 2011. From Hart, Moser, et al. in preparation.



Barriers encountered in planning adaptation to climate change and extremes in California coastal communities. From Moser and Ekstrom (2012), forthcoming CEC report.



Strategies used to overcome barriers to climate adaptation. From Moser and Ekstrom (2012), forthcoming CEC report.

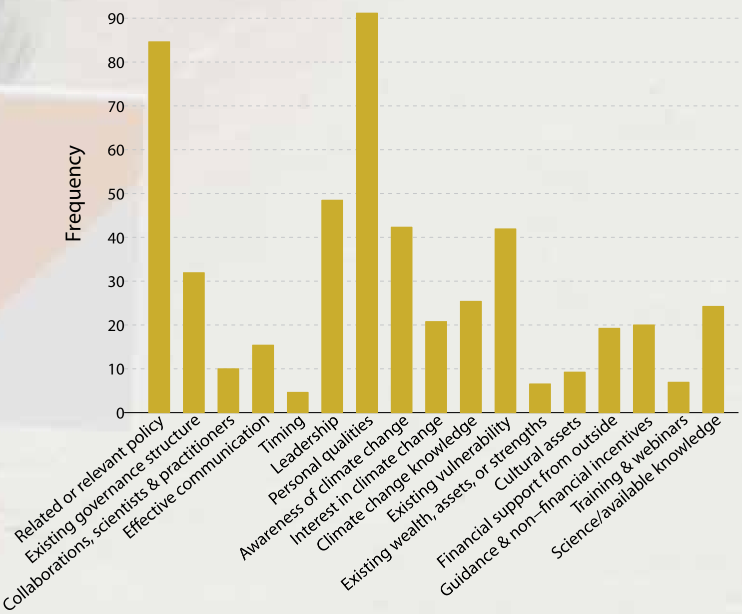
Current adaptation efforts

Many coastal California communities have started climate change adaptation efforts in the past five years, although they are generally still at an early stage. However, a recent climate extreme was the least likely factor in getting the process started. Much more important was an opportune round of community planning, for example, a general development plan or local coastal plan, which adaptation ideas could be incorporated into. This is probably because structured planning efforts are funded activities, and provide a way to add adaptation into existing management efforts.

The biggest barriers to adaptation efforts are institutional and governmental, not technical or scientific. Lack of time, staff, and money are common. However local attitudes, values, and motivations are often a significant barrier as well. On the plus side, the majority of barriers are of local origin, and so addressable in a local context. Fundamentally, adaptation depends on people willing to do something new and take a risk. Lack of technical or scientific solutions to the problems was far down the list of barriers compared to political, institutional, and people issues.

Strong leadership and knowledgeable staff made the biggest difference in overcoming the barriers to adaptation. It also was motivational when there was a local perception of vulnerability to climate extremes or change, for example, from a recent flood or drought. This brought people's attention to the issue and let them imagine what the future might hold.

Finally, even in the richest areas of California, economic barriers to adaptation are significant. This is not surprising given the recent economic downturn. Adaptation to date consists largely of strategies for overcoming barriers to change rather than structural changes on the ground.



Aids and advantages that helped avoid and overcome barriers to adaptation. From Moser and Ekstrom (2012).

Contributors:

Susanne C. Moser (Susanne Moser Research & Consulting and Stanford University); Julie Ekstrom (UC Berkeley); Ruth Langridge (UC Santa Cruz).

For more information:

Moser, S. C., and Ekstrom, J. A. (2012): Identifying and Overcoming Barriers to Climate Change Adaptation in San Francisco Bay: Results from Case Studies. PIER Research Report CEC-500-2012-XXX, forthcoming.

Background image courtesy FEMA/Adam Dubrowa

Closing Remarks

The findings discussed in the California Climate Extremes Workshop show how climate change will not only shift average conditions but may "load the dice" toward more frequent or intense extreme events. Although precise details of future extremes cannot be known, history and model projections provide a general picture of their characteristics. Clearly, extremes need to be heavily weighted in planning for changes—for example, a single high water storm event may, in just a few days, inflict high costs that are exacerbated by decades of gradual sea level rise. The downside risk of these events underscores the need to investigate scenarios of climate change at a level of detail that includes these infrequent but damaging events.

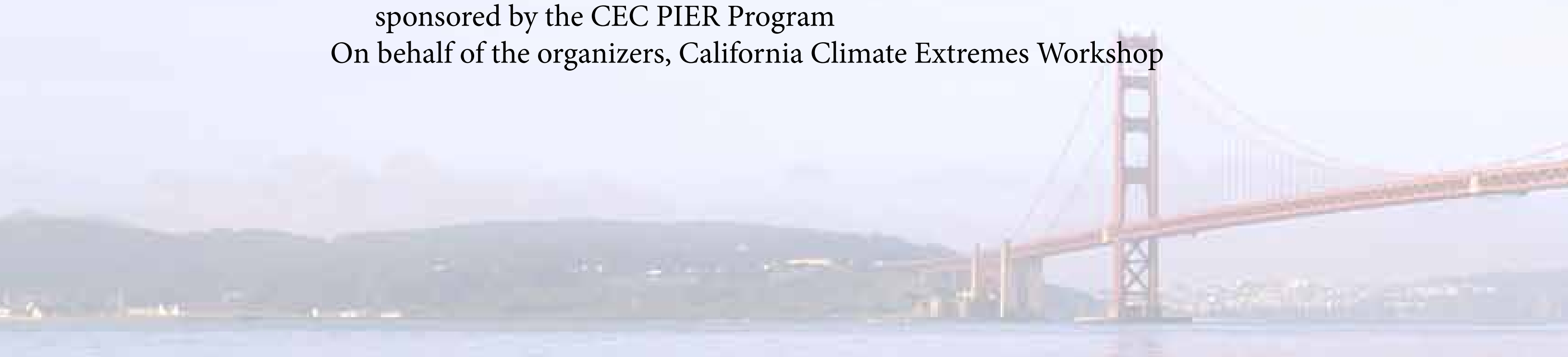
Some aspects of climate change, including warming and sea level rise, are reasonably well known, although there is still a substantial range of possible outcomes. However, holes in our knowledge remain. Some gaps stem from uncertainty in how global climate change will unfold. For example, we are still grappling with the pattern of precipitation changes over western North America. But as our colleagues at this workshop emphasized, there is much to be learned at regional levels—not only about climate, but about the physical, biological and social environment the climate acts upon.

Results presented in the Workshop begin to unveil regional and local specifics involved in extreme climate impacts. Further progress will require careful long term monitoring, not only of physical climate but also key impact variables in ecosystems, economics, human health, and many other sectors. Progress also requires a better understanding of the mechanisms that create extreme climate events in order to improve models, the tools we use to look forward.

Extreme events impact many sectors. The Workshop brought together physical scientists, biologists, social scientists, economists, and representatives from government, private industry, and the local community. The pathway to effective planning and action must navigate uncertainties in physical and biological changes, yet that is only part of the challenge. Human behavior must also be factored in. California is known for using science to explore options and inform policy. This tradition will be ever more important as changes grow and continue to unfold.

Dan Cayan

California Nevada Applications Program, a NOAA RISA Center
California Climate Change Center at Scripps Institution of Oceanography, sponsored by the CEC PIER Program
On behalf of the organizers, California Climate Extremes Workshop



"The great central valley of the state is under water—the Sacramento and San Joaquin valleys—a region 250 to 300 miles long and an average of at least twenty miles wide...Thousands of farms are entirely under water—cattle starving and drowning.

"It is supposed that over one-fourth of all the taxable property of the state has been destroyed. The legislature has left the capital and has come here, that city being under water.

"Nearly every house and farm over this immense region is gone. There was such a body of water—250 to 300 miles long and 20 to 60 miles wide, the water ice cold and muddy—that the winds made high waves which beat the farm homes in pieces...But the spirits of the people are rising, and it will make them more careful in the future. The experience was needed. Had this flood been delayed for ten years the disaster would have been more than doubled."

—William Brewer

Excerpts from letters during the Geological Survey of California
Jan 31-Feb 10, 1862

SCRIPPS INSTITUTION OF OCEANOGRAPHY

UC San Diego