

Climate Change Indicators

Recent Research on Climate Change:

A bibliography with an emphasis on California

August 2018



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RECENT RESEARCH ON CLIMATE CHANGE:

A bibliography with an emphasis on California

August 2018

The Office of Environmental Health Hazard Assessment compiled this bibliography to support the preparation of its May 2018 report, Indicators of Climate Change in California

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Introduction

The Office of Environmental Health Hazard Assessment (OEHHA) continually monitors the scientific literature, publications of research organizations, governmental entities and academia, and other sources for information relating to climate change and its impacts on California. This bibliography is a compilation of selected publications presenting observations and new or emerging scientific information on climate change with an emphasis on California. This bibliography supports OEHHA's efforts to compile a periodic report on indicators of climate change in California (OEHHA, 2018), and is made available as a resource for environmental and public health agencies, the research community, non-government organizations, and the public.

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

This bibliography covers research published from 2012 to early 2018 (this period overlaps with literature summarized by OEHHA in earlier bibliographies [OEHHA, 2013; 2015; 2016]). No references from the earlier bibliographies are repeated in this document.

Identifying and selecting references

OEHHA identified publications describing past and current data or new or modified scientific understanding about changes in climate, the causes or drivers of climate change, and its impacts. OEHHA conducted literature searches and monitored environmental newsletters, websites of research institutions and government entities and the popular press (see Appendix for methodology). Publications that relate to California were targeted, although references that cover other geographic areas were included if their findings are relevant to California. Specifically excluded are references that primarily present future scenarios or modelled projections, or that mainly discuss mitigation or adaptation measures.

Structure of the report

References are organized into five categories described below. Except for the first one, the categories correspond to the structure of the climate change indicators report.

Authoritative reports

Certain national and international organizations are generally recognized to have established expertise in topics relating to climate change or relevant physical or biological scientific disciplines. Reports, assessments or periodic updates published by these entities on climate change-related topics are included in this category.

Drivers of climate change

The climate system is influenced by its own internal dynamics and by changes in external factors or “forcings.” Natural forcings (e.g., solar radiation and volcanic eruptions) and human-induced forcings (e.g., changes in atmospheric composition due to fossil fuel combustion and land use) alter the energy balance of the climate system and are drivers of climate change. Land use can affect climate by altering the amount of solar radiation that is reflected by such surfaces back into space.

Changes in climate

Climate, which is generally defined as “average weather,” is usually described in terms of the mean and variability of temperature, precipitation, and wind over a period of time.

Impacts of climate on physical systems

Climate is a key factor affecting the characteristics of natural physical systems. These systems include snow, glaciers, ice, water vapor, streams, rivers, lakes and the ocean. Examples of impacts include sea level rise, increasing ocean and lake water temperatures, and changes in snowmelt runoff.

Impacts of climate on biological systems

Terrestrial, marine and freshwater biological systems are strongly influenced by climatic conditions. Changes in climate can impact humans (e.g., increased deaths during heat waves), vegetation (e.g., wildfires and vegetation distribution shifts) and wildlife (e.g., small mammal population range shifts).

The citations

The categories listed above are further divided into subcategories. Within these subcategories, the references are arranged by publication date, from the earliest to most recent. For each reference, the following are provided: a full citation; a web address for accessing the publication or its abstract; the geographic location (e.g., California, northern Pacific Ocean); the type of reference (e.g., report, research paper); and the publication’s abstract (or an excerpt from the abstract, introduction, foreword, or background, or highlights of the publication). References may cover information pertinent to multiple categories or subcategories.

References:

IPCC (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

OEHHA (2018). *Indicators of Climate Change in California*. Office of Environmental Health Hazard Assessment, California Environmental Protection Agency.

Authoritative Reports

This chapter presents publications by national and international governmental or scientific organizations authoritative in topics relating to climate change or relevant physical or biological scientific disciplines. Examples of such organizations are the National Oceanic and Atmospheric Administration (NOAA), the World Meteorological Organization (WMO) and the US Global Change Research Program.

Global

An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity. Secretariat of the Convention on Biological Diversity (2014). CBD Technical Series No. 75. <https://www.cbd.int/doc/publications/cbd-ts-75-en.pdf>

Geographic Location: Global

Type of Reference: Report

From the Foreword and Executive Summary: This report synthesizes the best available and most up-to-date information on the impacts of changing ocean pH on the health of the world's oceans. Among other findings, the report notes that ocean acidification has increased by around 26 percent since pre-industrial times and that, based on historical evidence, recovery from such changes in ocean pH can take many thousands of years. The report outlines how ocean acidification impacts the physiology, sensory systems and behavior of marine organisms and undermines ecosystem health. It shows that impacts due to ocean acidification are already underway in some areas and that future projected impacts could have drastic irreversible impacts on marine ecosystems. Despite the growing body of information on ocean acidification, the report points out key knowledge gaps and, in light of the many complex interactions related to ocean chemistry, stresses the difficulty in assessing how future changes to ocean pH will affect marine ecosystems, food webs and ecosystems, and the goods and services they provide.

Harmful Algal Blooms: A Scientific Summary for Policy Makers. Kudela RM, Berdalet E, Bernard S, Burford M, Fernand L et al. (2015). IOC/UNESCO, Paris (IOC/INF-1320). <http://unesdoc.unesco.org/images/0023/002334/233419e.pdf>

Geographic Location: Global

Type of Reference: Report

Summary and Key Points:

- Harmful Algal Blooms (HABs) result from noxious and/or toxic algae that cause direct and indirect negative impacts to aquatic ecosystems, coastal resources, and human health.



- HABs are present in nearly all aquatic environments (freshwater, brackish and marine), as naturally occurring phenomena.
- Many HABs are increasing in severity and frequency, and biogeographical range. Causes are complex, but in some cases can be attributed to climate change and human impacts, including eutrophication, habitat modification, and human-mediated introduction of exogenous species.
- There is no plan, and no realistic possibility, to eliminate HABs and/or their dependent consequences. Decades of research and monitoring have, however, improved our understanding of HAB events, leading to better monitoring and prediction strategies.
- HABs are a worldwide phenomenon requiring an international understanding leading ultimately to local and regional solutions. Continued progress in research, management, mitigation, and prediction of HABs benefits from international coordination. In this spirit, the international community has developed programmes sponsored by the Intergovernmental Oceanographic Commission (IOC) and Scientific Committee on Oceanic Research (SCOR) to coordinate international HAB research, framework activities, and capacity building.
- HABs are recognized as one facet of complex ecosystem interactions with human society. HAB research, monitoring, and management must be closely integrated with policy decisions that affect our global oceans.
- New initiatives, such as GlobalHAB sponsored by IOC and SCOR, will continue to provide the mechanisms to further understand, predict, and mitigate HABs. Research, management, and mitigation efforts directed towards HABs must be coordinated with other local, national, and international efforts focused on food and water security, human and ecosystem health, ocean observing systems, and climate change.

WMO Greenhouse Gas Bulletin. The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2015. World Meteorological Organization (2016). https://library.wmo.int/opac/doc_num.php?explnum_id=3084.

Geographic Location: Global

Type of Reference: Report

Executive Summary: The latest analysis of observations from the WMO Global Atmosphere Watch (GAW) Programme shows that globally averaged surface mole fractions calculated from this *in situ* network for carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) reached new highs in 2015, with CO₂ at 400.0±0.1 ppm, CH₄ at 1845±2 ppb and N₂O at 328.0±0.1 ppb. These values constitute, respectively, 144%, 256% and 121% of pre-industrial (before 1750) levels. It is predicted that 2016 will be the first year in which CO₂ at the Mauna Loa Observatory remains above 400 ppm all year, and hence for many generations. The increase of CO₂ from 2014 to 2015 was larger than that observed from 2013 to 2014 and that averaged over the past 10 years. The El Niño event in 2015 contributed to the increased growth rate through complex two-way interactions between climate change and the carbon cycle. The increase of



CH₄ from 2014 to 2015 was larger than that observed from 2013 to 2014 and that averaged over the last decade. The increase of N₂O from 2014 to 2015 was similar to that observed from 2013 to 2014 and greater than the average growth rate over the past 10 years. The National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Gas Index shows that from 1990 to 2015 radiative forcing by long-lived greenhouse gases (LLGHGs) increased by 37%, with CO₂ accounting for about 80% of this increase.

WMO Greenhouse Gas Bulletin. The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2016. World Meteorological Organization (2017). https://library.wmo.int/opac/doc_num.php?explnum_id=4022

Geographic Location: Global

Type of Reference: Report

Executive Summary: The latest analysis of observations from the WMO Global Atmosphere Watch (GAW) Programme shows that globally averaged surface mole fractions calculated from this *in situ* network for CO₂, methane (CH₄) and nitrous oxide (N₂O) reached new highs in 2016, with CO₂ at 403.3 ± 0.1 ppm, CH₄ at 1 853 ± 2 ppb and N₂O at 328.9 ± 0.1 ppb. These values constitute, respectively, 145%, 257% and 122% of pre-industrial (before 1750) levels. The record increase of 3.3 ppm in CO₂ from 2015 to 2016 was larger than the previous record increase, observed from 2012 to 2013, and the average growth rate over the last decade. The El Niño event in 2015/2016 contributed to the increased growth rate through complex two-way interactions between climate change and the carbon cycle. The increase of CH₄ from 2015 to 2016 was slightly smaller than that observed from 2014 to 2015, but larger than the average over the last decade. The increase of N₂O from 2015 to 2016 was also slightly smaller than that observed from 2014 to 2015 and the average growth rate over the past 10 years. The National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Gas Index (AGGI) shows that from 1990 to 2016, radiative forcing by long-lived greenhouse gases (LLGHGs) increased by 40%, with CO₂ accounting for about 80% of this increase.

WMO Statement on the State of the Global Climate in 2016. World Meteorological Organization (2017). WMO-No. 1189.

https://library.wmo.int/doc_num.php?explnum_id=3414

Geographic Location: Global

Type of Reference: Report

Executive Summary: Warming continued in 2016, setting a new temperature record of approximately 1.1 °C above the pre-industrial period, and 0.06 °C above the previous highest value set in 2015. Carbon dioxide (CO₂) reached new highs at 400.0 ± 0.1 ppm



in the atmosphere at the end of 2015. Global sea-ice extent dropped more than 4 million km² below average – an unprecedented anomaly – in November. Global sea levels rose strongly during the 2015/2016 El Niño, with the early 2016 values making new records.

The powerful 2015/2016 El Niño event exerted a strong influence on the climate and societies against a background of long-term climate change. Severe droughts affected agriculture and yield production in many parts of the world, particularly in southern and eastern Africa and parts of Central America, where several million people experienced food insecurity and hundreds of thousands were displaced internally, according to reports from the World Food Programme (WFP), the United Nations Food and Agriculture Organization (FAO), the United Nations High Commissioner for Refugees (UNHCR) and the International Organization for Migration (IOM).

Hurricane Matthew in the North Atlantic led to the most damaging meteorological disaster, with Haiti sustaining the heaviest casualties. There were also major economic losses in the United States and elsewhere in the region. Flooding severely affected eastern and southern Asia with hundreds of lives lost, hundreds of thousands of people displaced and severe economic damage. Wet conditions led to good crop production in many parts of the Sahel, with record yields reported in Mali, Niger and Senegal.¹

Detection and attribution studies have demonstrated that human influence on the climate has been a main driver behind the unequivocal warming of the global climate system observed since the 1950s, according to the Fifth Assessment Report of IPCC. Human influence has also led to significant regional temperature increases at the continental and subcontinental levels. Shifts of the temperature distribution to warmer regimes are expected to bring about increases in the frequency and intensity of extremely warm events.

¹ Unless stated otherwise, information on crop yields and production in this Statement is derived from *Crop Prospects and Food Situation*, No.4, December 2016, FAO

WMO Statement on the State of the Global Climate in 2017. World Meteorological Organization (2018). WMO-No. 1212.

https://library.wmo.int/doc_num.php?explnum_id=4453

Geographic Location: Global

Type of Reference: Report

Executive Summary: Global mean temperatures in 2017 were 1.1 °C ± 0.1 °C above pre-industrial levels. Whilst 2017 was a cooler year than the record-setting 2016, it was still one of the three warmest years on record, and the warmest not influenced by an El Niño event. The average global temperature for 2013–2017 is close to 1 °C above that for 1850–1900 and is also the highest five-year average on record. The world also continued to see rising sea levels, with some acceleration, and increasing



concentrations of greenhouse gases. The cryosphere continued its contraction, with Arctic and Antarctic sea ice shrinking.

The overall risk of heat-related illness or death has climbed steadily since 1980, with around 30% of the world's population now living in climatic conditions that deliver deadly temperatures at least 20 days a year.

There were many significant weather and climate events in 2017, including a very active North Atlantic hurricane season, major monsoon floods in the Indian subcontinent, and continuing severe drought in parts of east Africa. This contributed to 2017 being the year with the highest documented economic losses associated with severe weather and climate events. Extreme weather events continue to be rated by the World Economic Forum as amongst the most significant risks facing humanity, both in terms of likelihood and impact.

Massive internal displacement in the context of drought and food insecurity continues across Somalia. From November 2016 to December 2017, 892 000 drought-related displacements were recorded by the United Nations High Commissioner for Refugees (UNHCR).

In August and September 2017, the three major and devastating hurricanes that made landfall in the southern United States and in several Caribbean islands in rapid succession broke modern records for such weather extremes and for loss and damage.

The information used in this report is sourced from a large number of National Meteorological and Hydrological Services (NMHSs) and associated institutions, as well as Regional Climate Centres, the World Climate Research Programme (WCRP), the Global Atmosphere Watch (GAW) and Global Cryosphere Watch (GCW). Information has also been supplied by a number of other international organizations, including the Food and Agriculture Organization of the United Nations (FAO), the World Food Programme (WFP), the World Health Organization (WHO), the United Nations High Commissioner for Refugees (UNHCR), the International Organization for Migration (IOM), the International Monetary Fund (IMF), the United Nations International Strategy for Disaster Reduction (UNISDR) and the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO).

State of the Climate in 2015. Blunden J and Arndt DS (2016). *Bulletin of the American Meteorological Society*, **97**(8): S1–S275.

<https://journals.ametsoc.org/doi/pdf/10.1175/2016BAMSSStateoftheClimate.1>

Geographic Location: Global

Type of Reference: Journal article

Excerpt from the Abstract: In 2015, the dominant greenhouse gases released into Earth's atmosphere — carbon dioxide, methane, and nitrous oxide — all continued to



reach new high levels. At Mauna Loa, Hawaii, the annual CO₂ concentration increased by a record 3.1 ppm, exceeding 400 ppm for the first time on record. The 2015 global CO₂ average neared this threshold, at 399.4 ppm. Additionally, one of the strongest El Niño events since at least 1950 developed in spring 2015 and continued to evolve through the year. The phenomenon was far reaching, impacting many regions across the globe and affecting most aspects of the climate system.

Owing to the combination of El Niño and a long-term upward trend, Earth observed record warmth for the second consecutive year, with the 2015 annual global surface temperature surpassing the previous record by more than 0.1°C and exceeding the average for the mid- to late 19th century — commonly considered representative of preindustrial conditions by more than 1°C for the first time. Above Earth's surface, lower troposphere temperatures were near-record high. Across land surfaces, record to near-record warmth was reported across every inhabited continent.

Increasing temperatures have led to decreasing Arctic sea ice extent and thickness. On 25 February 2015, the lowest maximum sea ice extent in the 37-year satellite record was observed, 7% below the 1981–2010 average. Mean sea surface temperatures across the Arctic Ocean during August in ice-free regions, representative of Arctic Ocean summer anomalies, ranged from ~0°C to 8°C above average. As a consequence of sea ice retreat and warming oceans, vast walrus herds in the Pacific Arctic are hauling out on land rather than on sea ice, raising concern about the energetics of females and young animals. Increasing temperatures in the Barents Sea are linked to a community-wide shift in fish populations: boreal communities are now farther north, and long-standing Arctic species have been almost pushed out of the area.

Above average sea surface temperatures are not confined to the Arctic. Sea surface temperature for 2015 was record high at the global scale; however, the North Atlantic southeast of Greenland remained colder than average and colder than 2014. Global annual ocean heat content and mean sea level also reached new record highs. The Greenland Ice Sheet, with the capacity to contribute ~7 m to sea level rise, experienced melting over more than 50% of its surface for the first time since the record melt of 2012.

Other aspects of the cryosphere were remarkable. Alpine glacier retreat continued, and preliminary data indicate that 2015 is the 36th consecutive year of negative annual mass balance. Across the Northern Hemisphere, late-spring snow cover extent continued its trend of decline, with June the second lowest in the 49-year satellite record.

Overlaying a general increase in the hydrologic cycle, the strong El Niño enhanced precipitation variability around the world. In May, the United States recorded its all-time wettest month in its 121-year national record. Globally soil moisture was below average, terrestrial groundwater storage was the lowest in the 14-year record, and areas in “severe” drought rose from 8% in 2014 to 14% in 2015.



State of the Climate in 2016. Blunden J and Arndt DS (2017). *Bulletin of the American Meteorological Society*, **98**(8): S1–S277.

https://journals.ametsoc.org/doi/suppl/10.1175/2017BAMSSStateoftheClimate.1/suppl_file/10.1175_2017BAMSSStateoftheClimate.3.pdf

Geographic Location: Global

Type of Reference: Journal article

Excerpt from the Abstract: In 2016, the dominant greenhouse gases released into Earth's atmosphere — carbon dioxide, methane, and nitrous oxide — continued to increase and reach new record highs. The 3.5 ± 0.1 ppm rise in global annual mean carbon dioxide from 2015 to 2016 was the largest annual increase observed in the 58-year measurement record. The annual global average carbon dioxide concentration at Earth's surface surpassed 400 ppm (402.9 ± 0.1 ppm) for the first time in the modern atmospheric measurement record and in ice core records dating back as far as 800 000 years.

One of the strongest El Niño events since at least 1950 dissipated in spring, and a weak La Niña evolved later in the year. Owing at least in part to the combination of El Niño conditions early in the year and a long-term upward trend, Earth's surface observed record warmth for a third consecutive year, albeit by a much slimmer margin than by which that record was set in 2015. Above Earth's surface, the annual lower troposphere temperature was record high according to all datasets analyzed, while the lower stratospheric temperature was record low according to most of the in situ and satellite dataset.

In the Arctic the 2016 land surface temperature was 2.0°C above the 1981–2010 average, breaking the previous record of 2007, 2011, and 2015 by 0.8°C , representing a 3.5°C increase since the record began in 1900. The increasing temperatures have led to decreasing Arctic sea ice extent and thickness. On 24 March, the sea ice extent at the end of the growth season saw its lowest maximum in the 37-year satellite record, tying with 2015 at 7.2% below the 1981–2010 average. The September 2016 Arctic sea ice minimum extent tied with 2007 for the second lowest value on record, 33% lower than the 1981–2010 average. Arctic sea ice cover remains relatively young and thin, making it vulnerable to continued extensive melt. The mass of the Greenland Ice Sheet, which has the capacity to contribute ~ 7 m to sea level rise, reached a record low value. The onset of its surface melt was the second earliest, after 2012, in the 37-year satellite record.

Sea surface temperature was record high at the global scale, surpassing the previous record of 2015 by about 0.01°C . The global sea surface temperature trend for the 21st century-to-date of $+0.162^{\circ}\text{C decade}^{-1}$ is much higher than the longer term 1950–2016 trend of $+0.100^{\circ}\text{C decade}^{-1}$. Global annual mean sea level also reached a new record high, marking the sixth consecutive year of increase. Global annual ocean heat content saw a slight drop compared to the record high in 2015.



Alpine glacier retreat continued around the globe, and preliminary data indicate that 2016 is the 37th consecutive year of negative annual mass balance. Across the Northern Hemisphere, snow cover for each month from February to June was among its four least extensive in the 47-year satellite record.

The strong El Niño at the beginning of the year that transitioned to a weak La Niña contributed to enhanced precipitation variability around the world. In the United States, California had its first wetter-than-average year since 2012, after being plagued by drought for several years.

State of the Climate: Global Analysis – Annual (*for years 2016 and 2017*). National Oceanic and Atmospheric Administration, National Climatic Data Center.

Geographic Location: Global

Type of Reference: Interactive web-based report

Annual 2016 (<https://www.ncdc.noaa.gov/sotc/global/201613>)

Annual 2017 (<https://www.ncdc.noaa.gov/sotc/global/201713>)

Abstract: NOAA's National Climatic Data Center publishes an annual report summarizing climate-related data on both a global and national scale. (The annual national overview is described separately. Monthly reports are also available). The Global Analysis presents data for each calendar year, including global and regional temperatures, precipitation and a list of the year's top ten global weather or climate events.

Explaining extreme events of 2014 from a climate perspective. Herring SC, Hoerling MP, Kossin JP, Peterson TC, and Stott PA (2015). *Bulletin of the American Meteorological Society*, **96**(12): S1-S172. <http://dx.doi.org/10.1175/BAMS-ExplainingExtremeEvents2014.1>

Geographic Location: Global

Type of Reference: Report

Abstract: Understanding how long-term global change affects the intensity and likelihood of extreme weather events is a frontier science challenge. This fourth edition of explaining extreme events of the previous year (2014) from a climate perspective is the most extensive yet with 33 different research groups exploring the causes of 29 different events that occurred in 2014. A number of this year's studies indicate that human-caused climate change greatly increased the likelihood and intensity for extreme heat waves in 2014 over various regions. For other types of extreme events, such as droughts, heavy rains, and winter storms, a climate change influence was found in



some instances and not in others. This year's report also included many different types of extreme events. The tropical cyclones that impacted Hawaii were made more likely due to human-caused climate change. Climate change also decreased the Antarctic sea ice extent in 2014 and increased the strength and likelihood of high sea surface temperatures in both the Atlantic and Pacific Oceans. For western U.S. wildfires, no link to the individual events in 2014 could be detected, but the overall probability of western U.S. wildfires has increased due to human impacts on the climate.

Challenges that attribution assessments face include the often limited observational record and inability of models to reproduce some extreme events well. In general, when attribution assessments fail to find anthropogenic signals this alone does not prove anthropogenic climate change did not influence the event. The failure to find a human fingerprint could be due to insufficient data or poor models and not the absence of anthropogenic effects.

This year researchers also considered other human-caused drivers of extreme events beyond the usual radiative drivers. For example, flooding in the Canadian prairies was found to be more likely because of human land-use changes that affect drainage mechanisms. Similarly, the Jakarta floods may have been compounded by land-use change via urban development and associated land subsidence. These types of mechanical factors re-emphasize the various pathways beyond climate change by which human activity can increase regional risk of extreme events.

Explaining extreme events of 2015 from a climate perspective. Herring SC, Hoell A, Hoerling MP, Kossin JP, Schreck III CJ and Stott PA (2016). *Bulletin of the American Meteorological Society*, **97**(12): S1-S145. <http://dx.doi.org/10.1175/BAMS-ExplainingExtremeEvents2015.1>

Geographic Location: Global
Type of Reference: Report

Abstract: This fifth edition of explaining extreme events of the previous year (2015) from a climate perspective continues to provide evidence that climate change is altering some extreme event risk. Without exception, all the heat-related events studied in this year's report were found to have been made more intense or likely due to human-induced climate change, and this was discernible even for those events strongly influenced by the 2015 El Niño. Furthermore, many papers in this year's report demonstrate that attribution science is capable of separating the effects of natural drivers including the strong 2015 El Niño from the influences of long-term human-induced climate change.

Other event types investigated include cold winters, tropical cyclone activity, extreme sunshine in the United Kingdom, tidal flooding, precipitation, drought, reduced snowpack in the U.S. mountain west, arctic sea ice extent, and wildfires in Alaska. Two studies investigated extreme cold waves and monthly-mean cold conditions over



eastern North America during 2015, and find these not to have been symptomatic of human-induced climate change. Instead, they find the cold conditions were caused primarily by internally generated natural variability. One of these studies shows winters are becoming warmer, less variable, with no increase in daily temperature extremes over the eastern United States. Tropical cyclone activity was extreme in 2015 in the western North Pacific (WNP) as measured by accumulated cyclone energy (ACE). In this report, a study finds that human-caused climate change largely increased the odds of this extreme cyclone activity season. The 2015 Alaska fire season burned the second largest number of acres since records began in 1940. Investigators find that human-induced climate change has increased the likelihood of a fire season of this severity.

Confidence in results and ability to quickly do an attribution analysis depend on the “three pillars” of event attribution: the quality of the observational record, the ability of models to simulate the event, and our understanding of the physical processes that drive the event and how they are being impacted by climate change. A result that does not find a role for climate change may be because one or more of these three elements is insufficient to draw a clear conclusion. As these pillars are strengthened for different event types, confidence in the presence and absence of a climate change influence will increase.

This year researchers also link how changes in extreme event risk impact human health and discomfort during heat waves, specifically by looking at the role of climate change on the wet bulb globe temperature during a deadly heat wave in Egypt. This report reflects a growing interest within the attribution community to connect attribution science to societal impacts to inform risk management through “impact attribution.” Many will watch with great interest as this area of research evolves in the coming years.

Explaining extreme events of 2016 from a climate perspective. Herring SC, Christidis N, Hoell A, Kossin JP, Schreck III CJ and Stott PA (2018). *Bulletin of the American Meteorological Society*, **99**(1): S1-S157. <http://dx.doi.org/10.1175/BAMS-ExplainingExtremeEvents2016.1>

Geographic Location: Global

Type of Reference: Report

Abstract: This sixth edition of explaining extreme events of the previous year (2016) from a climate perspective is the first of these reports to find that some extreme events were not possible in a preindustrial climate. The events were the 2016 record global heat, the heat across Asia, as well as a marine heat wave off the coast of Alaska. While these results are novel, they were not unexpected. Climate attribution scientists have been predicting that eventually the influence of human-caused climate change would become sufficiently strong as to push events beyond the bounds of natural variability alone. It was also predicted that we would first observe this phenomenon for heat events where the climate change influence is most pronounced. Additional retrospective



analysis will reveal if, in fact, these are the first events of their kind or were simply some of the first to be discovered.

Last year, the editors emphasized the need for additional papers in the area of “impacts attribution” that investigate whether climate change’s influence on the extreme event can subsequently be directly tied to a change in risk of the socio-economic or environmental impacts. Several papers in this year’s report address this challenge, including Great Barrier Reef bleaching, living marine resources in the Pacific, and ecosystem productivity on the Iberian Peninsula. This is an increase over the number of impact attribution papers than in the past, and are hopefully a sign that research in this area will continue to expand in the future.

Other extreme weather event types in this year’s edition include ocean heat waves, forest fires, snow storms, and frost, as well as heavy precipitation, drought, and extreme heat and cold events over land. There were a number of marine heat waves examined in this year’s report, and all but one found a role for climate change in increasing the severity of the events. While human-caused climate change caused China’s cold winter to be less likely, it did not influence U.S. storm Jonas which hit the mid-Atlantic in winter 2016.

As in past years, the papers submitted to this report are selected prior to knowing the final results of whether human-caused climate change influenced the event. The editors have and will continue to support the publication of papers that find no role for human-caused climate change because of their scientific value in both assessing attribution methodologies and in enhancing our understanding of how climate change is, and is not, impacting extremes. In this report, twenty-one of the twenty-seven papers in this edition identified climate change as a significant driver of an event, while six did not. Of the 131 papers now examined in this report over the last six years, approximately 65% have identified a role for climate change, while about 35% have not found an appreciable effect. Looking ahead, we hope to continue to see improvements in how we assess the influence of human-induced climate change on extremes and the continued inclusion of stakeholder needs to inform the growth of the field and how the results can be applied in decision making. While it represents a considerable challenge to provide robust results that are clearly communicated for stakeholders to use as part of their decision-making processes, these annual reports are increasingly showing their potential to help meet such growing needs.

Handbook of Drought Indicators and Indices. World Meteorological Association and Global Water Partnership (2016). Integrated Drought Management Programme, World Meteorological Organization and Global Water Partnership. Geneva, Switzerland.
http://www.droughtmanagement.info/literature/GWP_Handbook_of_Drought_Indicators_and_Indices_2016.pdf

Geographic Location: Global

Type of Reference: Report



From the Introduction: The purpose of this handbook is to cover some of the most commonly used drought indicators/indices that are being applied across drought-prone regions, with the goal of advancing monitoring, early warning and information delivery systems in support of risk-based drought management policies and preparedness plans. These concepts and indicators/indices are outlined below in what is considered to be a living document that will evolve and integrate new indicators and indices as they come to light and are applied in the future. The handbook is aimed at those who want to generate indicators and indices themselves, as well as for those who simply want to obtain and use products that are generated elsewhere. It is intended for use by general drought practitioners (for example, meteorological/hydrological services and ministries, resource managers and other decision-makers at various levels) and aims to serve as a starting point, showing which indicators/indices are available and being put into practice around the world. In addition, the handbook has been designed with drought risk management processes in mind. However, this publication does not aim to recommend a 'best' set of indicators and indices. The choice of indicators/indices is based on the specific characteristics of droughts most closely associated with the impacts of concern to the stakeholders.

Highlights from the First Five-yearly Statement on the Status of the Global Climate. World Meteorological Organization (2016).

<https://public.wmo.int/en/resources/bulletin/highlights-from-first-five-yearly-statement-status-of-global-climate>

Geographic Location: Global

Type of Reference: Statement Highlights

Abstract: In the last few months, 2015's status as the warmest year on record has been making headlines around the world. The WMO annual Statements on the Status of the Global Climate are an important part of the global climate monitoring that has arrived at this conclusion. Now, for the first time, WMO has issued a five-yearly Statement on the Status of the Global Climate, covering 2011–2015.

Climate Change and Food Security: Risks and Responses. Food and Agriculture Organization of the United Nations (2016). <http://www.fao.org/3/a-i5188e.pdf>.

Geographic Location: Global

Type of Reference: Report

From the Introduction: "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (World Food Summit, 1996). This definition points to four dimensions of food security: availability of food,



accessibility (economically and physically), utilization (the way it is used and assimilated by the human body) and stability of these three dimensions. What is needed is not only enough food being produced globally – enough food is produced globally now but there are still almost 800 million hungry people – but that everybody has access to it, in the right quantity and quality, all the time.

Four out of the eight key risks identified by IPCC AR5 have close relations with or direct consequences to food security:

- Loss of rural livelihoods and income
- Loss of marine and coastal ecosystems, and livelihoods
- Loss of terrestrial and inland water ecosystems, and livelihoods
- Food insecurity and breakdown of food systems

This report brings together evidence from the IPCC, updated by the latest scientific findings and enriched by FAO's knowledge and experiences on the ground. It provides an overview of the cascading impacts of climate change on food security and nutrition, from physical impacts on agro-ecosystems to livelihoods and food security. It shows how the cascade of impacts acts on a series of vulnerabilities. It presents ways to adapt and build resilience to climate change to ensure food security and nutrition. It shows the importance to act now on climate change: to eliminate hunger; to enable the agriculture sectors to adapt to climate change; and to mitigate climate change in order to keep it at levels where it is still possible to ensure and safeguard everyone's food security and nutrition.

The aim of this paper is to provide an overview of the effects of climate change on food security and nutrition, intended as its four dimensions, and to explore ways to reduce negative impacts through adaptation and resilience. As such, the scope of the paper does not cover greenhouse gas (GHG) emissions from the agriculture sectors nor means to reduce them.

National

Characterizing Risk in Climate Change Assessments: Proceedings of a Workshop
National Academies Press (2016). <https://www.nap.edu/catalog/23569/characterizing-risk-in-climate-change-assessments-proceedings-of-a-workshop>

Geographic Location: Global

Type of Reference: Workshop Proceedings

From the Introduction: The U.S. Global Change Research Program (USGCRP) was established in 1990 to “assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change.” A key responsibility for the program is to conduct National Climate Assessments (NCAs) every 4 years. These assessments are intended to inform the nation about “observed changes in climate, the current status of the climate, and anticipated trends for the future.” The



USGCRP hopes that government entities from federal agencies to small municipalities, citizens, communities, and businesses will rely on these assessments of climate-related risks for planning and decision-making. The third NCA (NCA3) was published in 2014 and work on the fourth is beginning.

The USGCRP asked the Board on Environmental Change and Society of the National Academies of Sciences, Engineering, and Medicine to conduct a workshop to explore ways to frame the NCA4 and subsequent NCA reports in terms of risks to society. The workshop was intended to collect experienced views on how to characterize and communicate information about climate-related hazards, risks, and opportunities that will support decision makers in their efforts to reduce greenhouse gas emissions, reduce vulnerability to likely changes in climate, and increase resilience to those changes. *Characterizing Risk in Climate Change Assessments* summarizes the presentations and discussions from the workshop.

Climate Change Indicators in the United States, 2016. Fourth Edition.

US Environmental Protection Agency (2016).

https://www.epa.gov/sites/production/files/2016-08/documents/climate_indicators_2016.pdf

Geographic Location: United States

Type of Reference: Report

From “About this Report”: The U.S. Environmental Protection Agency (EPA) publishes this report to communicate information about the science and impacts of climate change, assess trends in environmental quality, and inform decision-making. Climate Change Indicators in the United States, 2016, is the fourth edition of a report first published by EPA in 2010. This report presents 37 indicators to help readers understand changes observed from long-term records related to the causes and effects of climate change, the significance of these changes, and their possible consequences for people, the environment, and society. While the indicators presented in this report do not cover all possible measures of the causes and effects of climate change, as might be found in the full body of scientific literature, they represent a wide-ranging set of indicators that show observed changes in the Earth’s climate system and several climate-relevant impacts.

Effects of Drought on Forests and Rangelands in the United States: A Comprehensive Science Synthesis.

US Department of Agriculture (2016).

https://www.srs.fs.usda.gov/pubs/gtr/gtr_wo93b.pdf

Geographic Location: United States

Type of Reference: Report



Abstract: This assessment provides input to the reauthorized National Integrated Drought Information System (NIDIS) and the National Climate Assessment (NCA), and it establishes the scientific foundation needed to manage for drought resilience and adaptation. Focal areas include drought characterization; drought impacts on forest processes and disturbances such as insect outbreaks and wildfire; and consequences for forest and rangeland values. Drought can be a severe natural disaster with substantial social and economic consequences. Drought becomes most obvious when large-scale changes are observed; however, even moderate drought can have long-lasting impacts on the structure and function of forests and rangelands without these obvious large-scale changes. Large, stand-level impacts of drought are already underway in the West, but all U.S. forests are vulnerable to drought. Drought-associated forest disturbances are expected to increase with climatic change. Management actions can either mitigate or exacerbate the effects of drought. A first principal for increasing resilience and adaptation is to avoid management actions that exacerbate the effects of current or future drought. Options to mitigate drought include altering structural or functional components of vegetation, minimizing drought-mediated disturbance such as wildfire or insect outbreaks, and managing for reliable flow of water.

Climate Science Special Report: Fourth National Climate Assessment, Volume I. US Global Change Research Program (2017). [Wuebbles DJ, Fahey DW, Hibbard KA, Dokken DJ, Stewart BC, and Maycock TK (Eds.)].
<https://science2017.globalchange.gov/>

Geographic Location: United States
Type of Reference: Report

Executive Summary: The climate of the United States is strongly connected to the changing global climate. The statements below highlight past, current, and projected climate changes for the United States and the globe.

Global annually averaged surface air temperature has increased by about 1.8°F (1.0°C) over the last 115 years (1901–2016). This period is now the warmest in the history of modern civilization. The last few years have also seen record-breaking, climate-related weather extremes, and the last three years have been the warmest years on record for the globe. These trends are expected to continue over climate timescales.

This assessment concludes, based on extensive evidence, that it is extremely likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence.

In addition to warming, many other aspects of global climate are changing, primarily in response to human activities. Thousands of studies conducted by researchers around the world have documented changes in surface, atmospheric, and oceanic



temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor.

For example, global average sea level has risen by about 7–8 inches since 1900, with almost half (about 3 inches) of that rise occurring since 1993. Human-caused climate change has made a substantial contribution to this rise since 1900, contributing to a rate of rise that is greater than during any preceding century in at least 2,800 years. Global sea level rise has already affected the United States; the incidence of daily tidal flooding is accelerating in more than 25 Atlantic and Gulf Coast cities.

Global average sea levels are expected to continue to rise—by at least several inches in the next 15 years and by 1–4 feet by 2100. A rise of as much as 8 feet by 2100 cannot be ruled out. Sea level rise will be higher than the global average on the East and Gulf Coasts of the United States.

Changes in the characteristics of extreme events are particularly important for human safety, infrastructure, agriculture, water quality and quantity, and natural ecosystems. Heavy rainfall is increasing in intensity and frequency across the United States and globally and is expected to continue to increase. The largest observed changes in the United States have occurred in the Northeast.

Heatwaves have become more frequent in the United States since the 1960s, while extreme cold temperatures and cold waves are less frequent. Recent record-setting hot years are projected to become common in the near future for the United States, as annual average temperatures continue to rise. Annual average temperature over the contiguous United States has increased by 1.8°F (1.0°C) for the period 1901–2016; over the next few decades (2021–2050), annual average temperatures are expected to rise by about 2.5°F for the United States, relative to the recent past (average from 1976–2005), under all plausible future climate scenarios.

The incidence of large forest fires in the western United States and Alaska has increased since the early 1980s and is projected to further increase in those regions as the climate changes, with profound changes to regional ecosystems.

Annual trends toward earlier spring melt and reduced snowpack are already affecting water resources in the western United States and these trends are expected to continue. Under higher scenarios, and assuming no change to current water resources management, chronic, long-duration hydrological drought is increasingly possible before the end of this century.

The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse gases (especially carbon dioxide) emitted globally. Without major reductions in emissions, the increase in annual average global temperature relative to preindustrial times could reach 9°F (5°C) or more by the end of this century. With significant reductions in emissions, the increase in annual average global temperature could be limited to 3.6°F (2°C) or less.

The global atmospheric carbon dioxide (CO₂) concentration has now passed 400 parts per million (ppm), a level that last occurred about 3 million years ago, when both global average temperature and sea level were significantly higher than today. Continued



growth in CO₂ emissions over this century and beyond would lead to an atmospheric concentration not experienced in tens to hundreds of millions of years. There is broad consensus that the further and the faster the Earth system is pushed towards warming, the greater the risk of unanticipated changes and impacts, some of which are potentially large and irreversible.

The observed increase in carbon emissions over the past 15–20 years has been consistent with higher emissions pathways. In 2014 and 2015, emission growth rates slowed as economic growth became less carbon-intensive. Even if this slowing trend continues, however, it is not yet at a rate that would limit global average temperature change to well below 3.6°F (2°C) above preindustrial levels.

Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016.

U.S. Environmental Protection Agency (2018).

<https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016>

Geographic Location: United States

Type of Reference: Report

From the Executive Summary: An emissions inventory that identifies and quantifies a country's primary anthropogenic sources and sinks of greenhouse gases is essential for addressing climate change. This inventory adheres to both (1) a comprehensive and detailed set of methodologies for estimating sources and sinks of anthropogenic greenhouse gases, and (2) a common and consistent format that enables Parties to the United Nations Framework Convention on Climate Change (UNFCCC) to compare the relative contribution of different emission sources and greenhouse gases to climate change.

In 1992, the United States signed and ratified the UNFCCC. As stated in Article 2 of the UNFCCC, “The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

Parties to the Convention, by ratifying, “shall develop, periodically update, publish and make available...national inventories of anthropogenic emissions by sources and removals by sinks of all greenhouse gases not controlled by the Montreal Protocol, using comparable methodologies...” The United States views this report as an opportunity to fulfill these commitments. This chapter summarizes the latest information on U.S. anthropogenic greenhouse gas emission trends from 1990 through 2016. To



ensure that the U.S. emissions inventory is comparable to those of other UNFCCC Parties, the estimates presented here were calculated using methodologies consistent with those recommended in the *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

California

The West Coast Ocean Acidification and Hypoxia Science Panel: Major Findings, Recommendations, and Actions. Chan F, Boehm AB, Barth JA, Chornesky EA, Dickson AG, et al. (2016). California Ocean Science Trust, Oakland, California, USA. <http://westcoastoah.org/wp-content/uploads/2016/04/OAH-Panel-Key-Findings-Recommendations-and-Actions-4.4.16-FINAL.pdf>

Geographic Location: Pacific Ocean/West Coast

Type of Reference: Report

From the Introduction: Global carbon dioxide (CO₂) emissions over the past two centuries have altered the chemistry of the world's oceans, threatening the health of coastal ecosystems and industries that depend on the marine environment. This fundamental chemical alteration is known as ocean acidification (OA), a phenomenon driven by the oceans absorbing approximately one-third of atmospheric CO₂ generated through human activities. Scientists initially observed the impacts of OA on calcifying marine organisms that were having difficulty forming their shells, but additional evidence now indicates that growth, survival and behavioral effects linked to OA extend throughout food webs, threatening coastal ecosystems, and marine-dependent industries and human communities (see Appendix A). Although OA is a global phenomenon, emerging research indicates that, among coastal zones around the world, the West Coast of North America will face some of the earliest, most severe changes in ocean carbon chemistry. The threats posed by OA's progression will be further compounded by other dimensions of global climate change, such as the intensification and expansion of low dissolved oxygen – or hypoxic – zones. In the coming decades, the impacts of ocean acidification and hypoxia (OAH), which are already being felt across West Coast systems, are projected to grow rapidly in intensity and extent. Even if atmospheric CO₂ emissions are stabilized today, many of the ongoing chemical changes to the ocean are already “locked in” and will continue to occur for the next several decades. Given these challenges, decision-makers must act decisively and in concert now. In an effort to develop the scientific foundation necessary for West Coast managers to take informed action, the California Ocean Protection Council in 2013 asked the California Ocean Science Trust to establish and coordinate a scientific advisory panel in collaboration with California's ocean management counterparts in Oregon, Washington and British Columbia. The resulting West Coast Ocean Acidification and Hypoxia Science Panel, comprised of 20 leading scientific experts (see V. The Panelists, page 32), was charged with summarizing the current state of knowledge and developing scientific consensus about available management options to address OAH on the West Coast. This document, "Major Findings, Recommendations,



and Actions" of the Panel, summarizes the Panel's work and presents Actions that can be taken now to address OAH. The appendices to this document contain a series of two-page synopses that provide more detail on many of the key concepts that are mentioned in the main body. In addition to this document, the Panel has produced a number of longer supporting documents intended for agency program managers and technical audiences (see VI. Additional Panel Products Supporting the "Major Findings, Recommendations, and Actions," page 36).

California Current Integrated Ecosystem Assessment (CCIEA) State of the California Current Report. A Report of the NOAA CCIEA Team to the Pacific Fishery Management Council. Garfield TD and Harvey C, (Eds). (2016)
<https://www.pcouncil.org/ecosystem-based-management/annual-state-of-the-california-current-ecosystem/>

Geographic Location: Pacific Ocean/West Coast California
Type of Reference: Report

Highlights:

- Due to the record high sea surface temperature anomalies in both the northeast Pacific and the region off Baja California and the development of the third largest El Niño this century, for the 2014–2015 period the California Current Ecosystem can be classified as lower productivity at almost every trophic level. Oceanographic conditions, represented by MEI, PDO and NPGO indices, indicated warmer conditions throughout.
- The northern copepod index decreased off of Newport, indicating lower energy content for higher trophic levels.
- High energy forage species were at low levels, while forage species with low and intermediate energy content were patchy; catches of young of the year rockfish and market squid were very high South of Cape Mendocino.
- Pacific salmon faced additional stresses due to drought, warm weather, warm streams and 95% below-normal snow-water equivalent storage.
- Unusual mortality events for California sea lions and Guadalupe Fur Seals, as well as an unusually large, coast-wide common murre wreck, are further evidence of overall lower productivity in the California Current Ecosystem.
- Commercial fishing landings remained high, driven mainly by landings of Pacific hake and coastal pelagic species.
- Newly developed indicators of coastal community vulnerability show that fishery-dependent communities experienced increasing socioeconomic vulnerability from 2000 to 2010.



California Current Integrated Ecosystem Assessment (CCIEA) State of the California Current Report. A report of the NOAA CCIEA Team to the Pacific Fishery Management Council. Harvey C and Garfield T (Eds.). (2017)

<https://www.pcouncil.org/ecosystem-based-management/annual-state-of-the-california-current-ecosystem/>

Geographic Location: Pacific Ocean/West Coast California

Type of Reference: Report

Highlights:

- Following the unprecedented warm anomaly of 2013-2016 and the major El Niño event of 2015-2016, most large-scale climate indices for the Northeast Pacific (ONI, PDO and NPGO) have returned to relatively neutral values.
- Coastal upwelling was relatively weak in the northern California Current throughout 2016; upwelling along the central coast was initially weak but strengthened by summer, while upwelling on southern coast was average to above-average.
- Snowpack rebounded from the extremely low 2015, although much of the 2016 snow melted rapidly, leading to low streamflows; so far, 2017 precipitation is well above average.
- Copepod biomass off Newport, OR remains dominated by relatively energy-poor species as of fall 2016.
- The spring/summer pelagic forage community was once again highly diverse in 2016. Surveys experienced poor catches of sardine, market squid and krill. However, surveys had high but patchy catches of juvenile rockfish, juvenile hake and anchovy.
- Chinook salmon escapements through 2014-2015 varied by region and life history type. We remain concerned about environmental conditions for Chinook and coho salmon that went to sea over the past several years.
- California sea lions at the San Miguel Island colony experienced very poor foraging conditions to support pups in the 2015 cohort, though preliminary evidence suggests better conditions for the 2016 pups.
- Commercial fishing landings and revenues declined markedly in 2015, driven mainly by drops in harvest of Pacific hake, coastal pelagic species, and crabs.

Ecosystem Status Report of the California Current for 2017: A Summary of Ecosystem Indicators Compiled by the California Current Integrated Ecosystem Assessment Team (CCIEA). Harvey C, Garfield N, Williams G, Andrews K, Barceló C, et al. (2017). (NOAA Technical Memorandum NMFS-NWFSC-139). Seattle, WA: Northwest Fisheries Science Center, U.S. Department of Commerce.

<https://repository.library.noaa.gov/view/noaa/16864>

Geographic Location: Pacific Ocean/West Coast California

Type of Reference: Report



From Executive Summary: This document is a companion to the ecosystem status report (ESR) provided by the California Current Integrated Ecosystem Assessment team (CCIEA) to the Pacific Fishery Management Council (PFMC) in March of 2017 (see above entry). The CCIEA team provides such reports annually, as one component of the overall CCIEA goal of providing quantitative, integrative science tools, products, and synthesis in support of ecosystem-based management of marine resources in the California Current.

California Current Integrated Ecosystem Assessment (CCIEA) California Current Ecosystem Status Report, 2018. A report of the NOAA CCIEA Team to the Pacific Fishery Management Council, March 9, 2018. Harvey C, Garfield T, Williams G, Tolimieri N and Hazen E (Eds.). <https://www.pcouncil.org/ecosystem-based-management/annual-state-of-the-california-current-ecosystem/>

Geographic Location: Pacific Ocean/West Coast California

Type of Reference: Report

Highlights: Climate, oceanographic and stream flow indicators suggest that the physical system is transitioning toward average or even La Niña conditions, following the marine heatwave (“Blob”) and major El Niño events of 2014-2016.

- Several ecological indicators in 2017 also point toward more average conditions:
 - The copepod community off Newport saw an increase in cool-water, lipid-rich species that are better for production of salmon
 - Some important forage species increased in the central and southern CCE
 - Sea lion pup growth at San Miguel Island was normal
 - There were no mass seabird mortality events
- However, there was lingering evidence of unfavorable conditions in 2017:
 - Persistent deep warm water remains in the northern portion of the system
 - Pyrosomes (warm-water salps) were extremely abundant in the northern and central CCE
 - Juvenile salmon catches were poor, and other indicators suggest that Chinook and coho salmon returns to the Columbia Basin will be below average in 2018
 - A major hypoxic event occurred on the shelf of the northern CCE in August-September
 - Reports of whale entanglements in fixed fishing gear were high for the fourth straight year; most reports involved crab gear, but some involved sablefish gear
- For the first time, the report includes highly migratory species indicators, related to biomass, recruitment, and management of protected species bycatch
- Social vulnerability can now be compared with the dependence of coastal communities on commercial fishing and on recreational fishing



- We find some evidence of threshold relationships (between sea lions and upwelling), but no support yet for an “early warning index” of major ecosystem state changes



Drivers of Climate Change

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

Greenhouse gases, black carbon and aerosols

Heat-trapping greenhouse gases are the major human-influenced drivers of climate change, with carbon dioxide (CO₂) being the largest contributor. Primarily emitted from the use of fossil fuels, annual average global concentrations of CO₂ exceeded a symbolic threshold of 400 parts per million (ppm) in 2015 for the first time since records began, a stark reminder that atmospheric greenhouse gases continue to increase. Given that CO₂ can remain in the atmosphere for thousands of years, levels will likely stay above the 400 ppm benchmark for generations to come. Global atmospheric levels of other greenhouse gases, including methane (CH₄), nitrous oxide (N₂O), and certain fluorinated gases (F-gases), have also risen. Black carbon, a "short-lived climate pollutant", is a powerful global warming agent and the second most important contributor to global warming after CO₂.

Black Carbon and the Regional Climate of California: Report to the Air Resources Board, Contract 08-323. Ramanathan V, Bahadur R and Ramanathan (2013).
<https://www.arb.ca.gov/research/rsc/3-8-13/item8dfr08-323.pdf>

Geographic Location: California

Type of Reference: Report

From Abstract: This report provides an assessment of the impact of black carbon on the regional radiative forcing and climate trends of California. The present regional integrated assessment is the first such attempt to estimate the radiative forcing of black carbon (BC) for one region (California in this case), both from a bottom-up approach (starting with emission inventory as input to aerosol-transport models) and a top-down approach (adopting satellite data in conjunction with ground based column averaged aerosol optical properties). This approach enabled us to uncover three unanticipated major findings: i). The first finding concerns the large decadal trends in BC concentrations largely in response to policies enacted to decrease PM emissions from diesel combustion. ii) The second is the discovery of the large effects of brown carbon (a form of organic carbon aerosols) on radiative forcing. iii) The third is the large



discrepancy between the top-down and the bottom-up approach of estimating radiative forcing and ways to close the gap.

Bounding the role of black carbon in the climate system: A scientific assessment.

Bond, TC, Doherty SJ, Fahey DW, Forster PM, Bernsten T, et al. (2013). *Journal of Geophysical Research: Atmospheres*, **118**(11): 5380 5552.

<http://dx.doi.org/10.1002/jgrd.50171>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Black carbon aerosol plays a unique and important role in Earth's climate system. Black carbon is a type of carbonaceous material with a unique combination of physical properties. This assessment provides an evaluation of black-carbon climate forcing that is comprehensive in its inclusion of all known and relevant processes and that is quantitative in providing best estimates and uncertainties of the main forcing terms: direct solar absorption; influence on liquid, mixed phase, and ice clouds; and deposition on snow and ice. These effects are calculated with climate models, but when possible, they are evaluated with both microphysical measurements and field observations. Predominant sources are combustion related, namely, fossil fuels for transportation, solid fuels for industrial and residential uses, and open burning of biomass. Total global emissions of black carbon using bottom-up inventory methods are 7500 Gg yr⁻¹ in the year 2000 with an uncertainty range of 2,000 to 29,000. However, global atmospheric absorption attributable to black carbon is too low in many models and should be increased by a factor of almost 3. After this scaling, the best estimate for the industrial-era (1750 to 2005) direct radiative forcing of atmospheric black carbon is +0.71 W m⁻² with 90% uncertainty bounds of (+0.08, +1.27) W m⁻². Total direct forcing by all black carbon sources, without subtracting the preindustrial background, is estimated as +0.88 (+0.17, +1.48) W m⁻². Direct radiative forcing alone does not capture important rapid adjustment mechanisms. A framework is described and used for quantifying climate forcings, including rapid adjustments. The best estimate of industrial-era climate forcing of black carbon through all forcing mechanisms, including clouds and cryosphere forcing, is +1.1 W m⁻² with 90% uncertainty bounds of +0.17 to +2.1 W m⁻². Thus, there is a very high probability that black carbon emissions, independent of co-emitted species, have a positive forcing and warm the climate. We estimate that black carbon, with a total climate forcing of +1.1 W m⁻², is the second most important human emission in terms of its climate forcing in the present-day atmosphere; only carbon dioxide is estimated to have a greater forcing. Sources that emit black carbon also emit other short-lived species that may either cool or warm climate. Climate forcings from co-emitted species are estimated and used in the framework described herein. When the principal effects of short-lived co-emissions, including cooling agents such as sulfur dioxide, are included in net forcing, energy-related sources (fossil fuel and biofuel) have an industrial-era climate forcing of +0.22 (−0.50 to +1.08) W m⁻² during the first year after emission. For a few of these sources, such as diesel engines and possibly residential biofuels, warming is strong enough that eliminating all short-lived emissions



from these sources would reduce net climate forcing (i.e., produce cooling). When open burning emissions, which emit high levels of organic matter, are included in the total, the best estimate of net industrial-era climate forcing by all short-lived species from black-carbon-rich sources becomes slightly negative (-0.06 W m^{-2} with 90% uncertainty bounds of -1.45 to $+1.29 \text{ W m}^{-2}$). The uncertainties in net climate forcing from black-carbon-rich sources are substantial, largely due to lack of knowledge about cloud interactions with both black carbon and co-emitted organic carbon. In prioritizing potential black-carbon mitigation actions, non-science factors, such as technical feasibility, costs, policy design, and implementation feasibility play important roles. The major sources of black carbon are presently in different stages with regard to the feasibility for near-term mitigation. This assessment, by evaluating the large number and complexity of the associated physical and radiative processes in black-carbon climate forcing, sets a baseline from which to improve future climate forcing estimates.

High-global warming potential F-gas emissions in California: Comparison of ambient-based versus inventory-based emission estimates, and implications of refined estimates. Gallagher G, Zhan T, Hsu YK, Gupta P, Pederson J, et al. (2014). *Environmental Science & Technology*, **48**(2): 1084-1093.
<http://dx.doi.org/10.1021/es403447v>

Geographic Location: California

Type of Reference: Research Paper

Background: To better inform greenhouse gas reduction policies, the California Air Resources Board (CARB) inventories annual emissions of high-global warming potential (GWP) fluorinated gases, the fastest growing sector of greenhouse gas (GHG) emissions globally. Baseline 2008 F-gas emissions estimates for selected chlorofluorocarbons (CFC-12), hydrochlorofluorocarbons (HCFC-22), and hydrofluorocarbons (HFC-134a) using an inventory-based methodology were compared to emissions estimates using ambient-based measurements. Significant discrepancies were found, with the inventory-based emissions methodology resulting in a systematic 42 percent under-estimation of CFC-12 emissions from older refrigeration equipment and older vehicles, and a systematic 114 percent over-estimation of emissions for HFC-134a, a refrigerant substitute for phased-out CFCs. Initial, inventory-based estimates for all F-gas emissions had assumed that equipment is no longer in service once it reaches its average lifetime of use. Revised emission estimates using improved models for equipment age at end-of-life, inventories, and leak rates specific to California resulted in F-gas emissions estimates in closer agreement to ambient-based measurements. The discrepancies between inventory-based estimates and ambient-based measurements were reduced from -42 percent to -6 percent for CFC-12, and from +114 percent to +9 percent for HFC-134a.



Climate change and the permafrost carbon feedback. Schuur EAG, McGuire AD, Schädel C, Grosse G, Harden JW, et al. (2015). *Nature*, **520**: 171-179.
<http://dx.doi.org/10.1038/nature14338>

Geographic Location: Arctic and sub-Arctic

Type of Reference: Review Article

Abstract: Large quantities of organic carbon are stored in frozen soils (permafrost) within Arctic and sub-Arctic regions. A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases carbon dioxide and methane. This feedback can accelerate climate change, but the magnitude and timing of greenhouse gas emission from these regions and their impact on climate change remain uncertain. Here we find that current evidence suggests a gradual and prolonged release of greenhouse gas emissions in a warming climate and present a research strategy with which to target poorly understood aspects of permafrost carbon dynamics.

Long-term trends in California mobile source emissions and ambient concentrations of black carbon and organic aerosol. McDonald BC, Goldstein AH, and Harley RA (2015). *Environmental Science & Technology*, **49**(8): 5178-5188.
<http://dx.doi.org/10.1021/es505912b>

Geographic Location: California

Type of Reference: Research Paper

Abstract: A fuel-based approach is used to assess long-term trends (1970-2010) in mobile source emissions of black carbon (BC) and organic aerosol (OA, including both primary emissions and secondary formation). The main focus of this analysis is the Los Angeles basin, where a long record of measurements is available to infer trends in ambient concentrations of BC and organic carbon (OC), with OC used here as a proxy for OA. Mobile source emissions and ambient concentrations have decreased similarly, reflecting the importance of on- and off-road engines as sources of BC and OA in urban areas. In 1970, the on-road sector accounted for ~90% of total mobile source emissions of BC and OA (primary + secondary). Over time as on-road engine emissions have been controlled, the relative importance of off-road sources has grown. By 2010, off-road engines were estimated to account for $37 \pm 20\%$ and $45 \pm 16\%$ of total mobile source contributions to BC and OA, respectively, in the Los Angeles area. This study highlights both the success of efforts to control on-road emission sources, and the importance of considering off-road engine and other VOC source contributions when assessing long-term emission and ambient air quality trends.



Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. Schädel C, Bader MK-F, Schuur EAG, Biasi C, Brahco R, et al. (2016). *Nature Climate Change*, 6(10): 950-953. <http://dx.doi.org/10.1038/nclimate3054>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Increasing temperatures in northern high latitudes are causing permafrost to thaw, making large amounts of previously frozen organic matter vulnerable to microbial decomposition. Permafrost thaw also creates a fragmented landscape of drier and wetter soil conditions that determine the amount and form (carbon dioxide (CO₂), or methane (CH₄)) of carbon (C) released to the atmosphere. The rate and form of C release control the magnitude of the permafrost C feedback, so their relative contribution with a warming climate remains unclear. We quantified the effect of increasing temperature and changes from aerobic to anaerobic soil conditions using 25 soil incubation studies from the permafrost zone. Here we show, using two separate meta-analyses, that a 10°Celsius increase in incubation temperature increased C release by a factor of 2.0 (95% confidence interval (CI), 1.8 to 2.2). Under aerobic incubation conditions, soils released 3.4 (95% CI, 2.2 to 5.2) times more C than under anaerobic conditions. Even when accounting for the higher heat trapping capacity of CH₄, soils released 2.3 (95% CI, 1.5 to 3.4) times more C under aerobic conditions. These results imply that permafrost ecosystems thawing under aerobic conditions and releasing CO₂ will strengthen the permafrost C feedback more than waterlogged systems releasing CO₂ and CH₄ for a given amount of C.

Atmospheric Measurement and Inverse Modeling to Improve Greenhouse Gas Emission Estimates. Fischer ML, Jeong S, Newman S, and Zhang J (2016). Lawrence Berkeley National Laboratory. <https://www.arb.ca.gov/research/apr/past/11-306.pdf>

Geographic Location: California

Type of Reference: Report

Excerpt from the Abstract: California has committed to an ambitious plan to reduce statewide greenhouse gas (GHG) emissions to 1990 levels by 2020 through Assembly Bill 32 (AB- 32), which requires accurate accounting of emissions for effective mitigation planning and verification of future emission reductions. Atmospheric GHG measurements from networks of towers can be combined with existing knowledge of emissions in a statistical inverse model -- weighing existing knowledge with the new observations -- to more accurately quantify GHG emissions. This study quantifies major anthropogenic GHGs including fossil fuel CO₂ (ffCO₂), methane (CH₄) and nitrous oxide (N₂O) emissions within California with a Bayesian inverse modeling framework, using atmospheric observations from an expanded GHG measurement network across California over multiple years. We first assess uncertainties in the transport model predictions using a combination of meteorological and carbon monoxide (CO) measurements. Comparison of predicted and measured CO mixing ratios at the four



towers during June 2013 – May 2014 yields near-unity slopes (predicted vs. measured) for the majority of sites and seasons, suggesting that the model simulations are sufficient to estimate emissions of CO and likely other GHGs across California to within 10%. The results of this study indicate that ffCO₂ emissions from central California are within 6% of the prior estimate (i.e., the estimate based on existing knowledge before measured data are taken into account), and that in the South Coast Air Basin (SoCAB) ffCO₂ emissions are within 11% of the prior estimate for that region. Combining results from the two regions (i.e., central California and SoCAB), ffCO₂ emissions are consistent to within approximately 10% of the prior estimate.

Reversal of global atmospheric ethane and propane trends largely due to US oil and natural gas production. Helmig D, Rossabi S, Hueber J, Tans P, Montzka SA, et al. (2016). *Nature Geoscience*, 9(7): 490-495. <http://dx.doi.org/10.1038/ngeo2721>

Geographic Location: Northern Hemisphere
Type of Reference: Research Paper

Abstract: Non-methane hydrocarbons such as ethane are important precursors to tropospheric ozone and aerosols. Using data from a global surface network and atmospheric column observations we show that the steady decline in the ethane mole fraction that began in the 1970s halted between 2005 and 2010 in most of the Northern Hemisphere and has since reversed. We calculate a yearly increase in ethane emissions in the Northern Hemisphere of 0.42 (± 0.19) Teragrams (Tg) yr⁻¹ between mid-2009 and mid-2014. The largest increases in ethane and the shorter-lived propane are seen over the central and eastern USA, with a spatial distribution that suggests North American oil and natural gas development as the primary source of increasing emissions. By including other co-emitted oil and natural gas non-methane hydrocarbons, we estimate a Northern Hemisphere total non-methane hydrocarbon yearly emission increase of 1.2 (± 0.8) Tg yr⁻¹. Atmospheric chemical transport modelling suggests that these emissions could augment summertime mean surface ozone by several nanomoles per mole near oil and natural gas production regions. Methane/ethane oil and natural gas emission ratios could suggest a significant increase in associated methane emissions; however, this increase is inconsistent with observed leak rates in production regions and changes in methane's global isotopic ratio.

Atmospheric methane evolution the last 40 years. Dalsoren SB, Myhre CL, Myhre G, Gomez-Pelaez AJ, Haslerud AS, et al. (2016). *Atmospheric Chemistry and Physics*, 16(5): 3099-3126. <http://dx.doi.org/10.5194/acp-16-3099-2016>

Geographic Location: Global
Type of Reference: Research Paper



Abstract: Observations at surface sites show an increase in global mean surface methane (CH₄) of about 180 parts per billion (ppb) (above 10 %) over the period 1984–2012. Over this period there are large fluctuations in the annual growth rate. In this work, we investigate the atmospheric CH₄ evolution over the period 1970–2012 with the Oslo CTM3 global Chemical Transport Model (CTM) in a bottom-up approach. We thoroughly assess data from surface measurement sites in international networks and select a subset suited for comparisons with the output from the CTM. We compare model results and observations to understand causes both for long-term trends and short-term variations. Employing the Oslo CTM3 model we are able to reproduce the seasonal and year to year variations and shifts between years with consecutive growth and stagnation, both at global and regional scales. The overall CH₄ trend over the period is reproduced, but for some periods the model fails to reproduce the strength of the growth. The observed growth after 2006 is overestimated by the model in all regions. This seems to be explained by a too strong increase in anthropogenic emissions in Asia, having global impact. Our findings confirm other studies questioning the timing or strength of the emission changes in Asia in the EDGAR v4.2 emission inventory over the last decades. The evolution of CH₄ is not only controlled by changes in sources, but also by changes in the chemical loss in the atmosphere and soil uptake. We model a large growth in atmospheric oxidation capacity over the period 1970–2012. In our simulations, the CH₄ lifetime decreases by more than 8% from 1970 to 2012, a significant shortening of the residence time of this important greenhouse gas. This results in substantial growth in the chemical CH₄ loss (relative to its burden) and dampens the CH₄ growth. The change in atmospheric oxidation capacity is driven by complex interactions between a number of chemical components and meteorological factors. In our analysis, we are able to detach the key factors and provide simple prognostic equations for the relations between these and the atmospheric CH₄ lifetime.

Methane emissions from the 2015 Aliso Canyon blowout in Los Angeles, California. Conley S, Franco G, Faloona I, Blake DR, Peischl J, and Ryerson TB (2016). *Science*, **351**(6279): 1317-1320. <http://dx.doi.org/10.1126/science.aaf2348>

Geographic Location: Aliso Canyon (Los Angeles), California

Type of Reference: Research Paper

Abstract: Single-point failures of the natural gas infrastructure can hamper deliberate methane emission control strategies designed to mitigate climate change. The 23 October 2015 blowout of a well connected to the Aliso Canyon underground storage facility in California resulted in a massive release of natural gas. Analysis of methane (CH₄) and ethane (C₂H₆) data from dozens of plume transects from 13 research aircraft flights between 7 Nov 2015 and 13 Feb 2016 shows atmospheric leak rates of up to 60 metric tonnes of CH₄ and 4.5 metric tonnes of C₂H₆ per hour. At its peak this blowout effectively doubled the CH₄ emission rate of the entire Los Angeles Basin, and in total released 97,100 metric tonnes of methane to the atmosphere.



Reducing urban greenhouse gas footprints. Pichler P-P, Zwickel T, Chavez A, Kretschmer T, Seddon J, et al. (2017). *Scientific Reports*, 7: 14659. <http://dx.doi.org/10.1038/s41598-017-15303-x>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Cities are economically open systems that depend on goods and services imported from national and global markets to satisfy their material and energy requirements. Greenhouse Gas (GHG) footprints are thus a highly relevant metric for urban climate change mitigation since they not only include direct emissions from urban consumption activities, but also upstream emissions, i.e. emissions that occur along the global production chain of the goods and services purchased by local consumers. This complementary approach to territorially-focused emission accounting has added critical nuance to the debate on climate change mitigation by highlighting the responsibility of consumers in a globalized economy. Yet, city officials are largely either unaware of their upstream emissions or doubtful about their ability to count and control them. This study provides the first internationally comparable GHG footprints for four cities (Berlin, Delhi NCT, Mexico City, and New York metropolitan area) applying a consistent method that can be extended to other global cities using available data. We show that upstream emissions from urban household consumption are in the same order of magnitude as cities' overall territorial emissions and that local policy leverage to reduce upstream emissions is larger than typically assumed.

California drought increases CO₂ footprint of energy. Hardin E, AghaKouchak A, Qomi MJA, Madani K, Tarroja B, et al. (2017). *Sustainable Cities and Society*, 28: 450-452. <http://dx.doi.org/10.1016/j.scs.2016.09.004>

Geographic Location: California

Type of Reference: Research Paper

Abstract: This paper discusses the CO₂ footprint of California's drought during 2012–2014. We show that California drought significantly increased CO₂ emissions of the energy sector by around 22 million metric tons, indicating 33% increase in the annual CO₂ emissions compared to pre-drought conditions. We argue that CO₂ emission of climate extremes deserve more attention, because their cumulative impacts on CO₂ emissions are staggering. Most countries, including the United States, do not have a comprehensive a nationwide energy-water plan to minimize their CO₂ emissions. We argue that developing a national water-energy plan under a changing climate should be prioritized in the coming years.



The impact of a severe drought on dust lifting in California's Owens Lake area.

Borlina C and Rennó (2017). *Scientific Reports*, 7: 1784.

<http://dx.doi.org/10.1038/s41598-017-01829-7>

Geographic Location: Owens Lake, California

Type of Reference: Research Paper

Abstract: Mineral dust aerosols are responsible for some of the largest sources of uncertainties in our current understanding of climate change. Here we show that a severe drought is having a significant impact in one of largest sources of mineral dust aerosols of the U.S., the Owens Lake area in California's southwest. Measurements of aerosol concentration (PM_{2.5} particle matter) in the Owens Lake salty playa show that the annual mean concentration of PM_{2.5} aerosol has been increasing steadily since the beginning of the current drought, with periods of high aerosol concentration increasing from 4 months in 2013 to 9 months in 2015. Interestingly, the PM_{2.5} aerosol concentration usually increases abruptly from less than ~0.05 milligrams per cubic meter (mg/m³) to ~0.25 mg/m³. This occurs when saltation events break salt crusts produced by the efflorescence of brine in the salty playa. The brine is produced by either rainfall or runoff water. Based on this observation, we hypothesize that there is an upper limit of ~0.25 mg/m³ in the annual mean PM_{2.5} aerosols concentration in the Owens Lake basin that might limit the impact of mineral dust aerosols on climate. Indeed, the upper annual limit of ~0.25 mg/m³ has been nearly reached during the current drought.

Warning signs for stabilizing global CO₂ emissions. Jackson RB, Le Qéré C, Andrew RM, Canadell JG, Peters CP, et al. (2017). *Environmental Research Letters*, 12(11): 110202. <http://dx.doi.org/10.1088/1748-9326/aa9662>

Geographic Location: Global

Type of Reference: Review Paper

Abstract: Carbon dioxide (CO₂) emissions from fossil fuels and industry comprise ~90% of all CO₂ emissions from human activities. For the last three years, such emissions were stable, despite continuing growth in the global economy. Many positive trends contributed to this unique hiatus, including reduced coal use in China and elsewhere, continuing gains in energy efficiency, and a boom in low-carbon renewables such as wind and solar. However, the temporary hiatus appears to have ended in 2017. For 2017, we project emissions growth of 2.0% (range: 0.8%–3.0%) from 2016 levels (leap-year adjusted), reaching a record 36.8 ± 2 gigatons CO₂. Economic projections suggest further emissions growth in 2018 is likely. Time is running out on our ability to keep global average temperature increases below 2 °C and, even more immediately, anything close to 1.5 °Celsius.



Large reductions in urban black carbon concentrations in the United States between 1965 and 2000. Kirchstetter TW, Preble CV, Hadley OL, Bond TC, and Apte JS (2017). *Atmospheric Environment*, **151**(7): 17-23.
<http://dx.doi.org/10.1016/j.atmosenv.2016.11.001>

Geographic Location: United States, including California
Type of Reference: Research Paper

Background: Long-term pollutant concentration trends can be useful for evaluating air quality effects of emission controls and historical transitions in energy sources. We employed archival records of coefficient of haze (COH), a now-retired measure of light-absorbing particulate matter, to re-construct historical black carbon (BC) concentrations at urban locations in the United States (U.S.). The following relationship between COH and BC was determined by reinstating into service COH monitors beside aethalometers for two years in Vallejo and one year in San Jose, California: $BC (\mu g\ m^{-3}) = 6.7COH + 0.1$, $R^2 = 0.9$. Estimated BC concentrations in ten states stretching from the East to West Coast decreased markedly between 1965 and 1980: 5-fold in Illinois, Ohio, and Virginia, 4-fold in Missouri, and 2.5-fold in Pennsylvania. Over the period from the mid-1960s to the early 2000s, annual average BC concentrations in New Jersey and California decreased from 13 to $2\ \mu g\ m^{-3}$ and 4 to $1\ \mu g\ m^{-3}$, respectively, despite concurrent increases in fossil fuel consumption from 1.6 to 2.1 EJ ($EJ = 10^{18}\ J$) in New Jersey and 4.2 to 6.4 EJ in California. New Jersey's greater reliance on BC-producing heavy fuel oils and coal in the 1960s and early 1970s and subsequent transition to cleaner fuels explains why the decrease was larger in New Jersey than California. Patterns in seasonal and weekly BC concentrations and energy consumption trends together indicate that reducing wintertime emissions – namely substituting natural gas and electricity for heavy fuel oil in the residential sector – and decreasing emissions from diesel vehicles contributed to lower ambient BC concentrations. Over the period of study, declining concentrations of BC, a potent and short-lived climate warming pollutant, contrast increasing fossil fuel carbon dioxide (CO_2) emissions in the U.S. Declining BC emissions may have had the benefit of mitigating some atmospheric warming driven by increased CO_2 emissions with complementary health benefits.

California Greenhouse Gas Emissions from 2000 to 2015 – Trends of Emissions and Other Indicators. California Air Resources Board (2017).
https://www.arb.ca.gov/cc/inventory/pubs/reports/2000_2015/ghg_inventory_trends_00-15.pdf

Geographic Location: California
Type of Reference: Report

Abstract: California's annual statewide greenhouse gas (GHG) emission inventory is an important tool for establishing historical emission trends and tracking California's progress in reducing GHGs. Most importantly, the GHG inventory is a critical piece, in



addition to California Global Warming Solutions Act (AB 32) program data, in demonstrating the state's progress in achieving the statewide GHG targets established by AB 32 (reduce emissions to the 1990 levels by 2020) and Senate Bill 32 (SB 32) (reduce emissions to 40% below the 1990 levels by 2030). The 2017 edition of the GHG inventory includes the emissions of the seven GHGs identified in AB 321 for years 2000 to 2015 and uses an inventory scope and framework consistent with international and national GHG inventory practices. Other programs within ARB address additional climate pollutants not included in AB 32 or the GHG inventory; for example, the Short-Lived Climate Pollutant (SLCP) Strategy³ includes black carbon and sulfur hexafluoride (SF₆).

Global carbon budget 2015. Le Qéré C, Moriarty R, Andrew RM, Canadell JG, Sitch S, et al. (2015). *Earth System Science Data*, 7(2): 349-396.
<http://dx.doi.org/10.5194/essd-7-349-2015>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Accurate assessment of anthropogenic carbon dioxide (CO₂) emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere is important to better understand the global carbon cycle, support the development of climate policies, and project future climate change. Here we describe data sets and a methodology to quantify all major components of the global carbon budget, including their uncertainties, based on the combination of a range of data, algorithms, statistics, and model estimates and their interpretation by a broad scientific community. We discuss changes compared to previous estimates as well as consistency within and among components, alongside methodology and data limitations. CO₂ emissions from fossil fuels and industry (EFF) are based on energy statistics and cement production data, while emissions from land-use change (ELUC), mainly deforestation, are based on combined evidence from land-cover-change data, fire activity associated with deforestation, and models. The global atmospheric CO₂ concentration is measured directly and its rate of growth (GATM) is computed from the annual changes in concentration. The mean ocean CO₂ sink (SOCEAN) is based on observations from the 1990s, while the annual anomalies and trends are estimated with ocean models. The variability in SOCEAN is evaluated with data products based on surveys of ocean CO₂ measurements. The global residual terrestrial CO₂ sink (SLAND) is estimated by the difference of the other terms of the global carbon budget and compared to results of independent dynamic global vegetation models forced by observed climate, CO₂, and land-cover change (some including nitrogen–carbon interactions). We compare the mean land and ocean fluxes and their variability to estimates from three atmospheric inverse methods for three broad latitude bands. All uncertainties are reported as $\pm 1\sigma$, reflecting the current capacity to characterise the annual estimates of each component of the global carbon budget. For the last decade available (2005–2014), EFF was 9.0 ± 0.5 GtC yr⁻¹, ELUC was 0.9 ± 0.5 GtC yr⁻¹, GATM was 4.4 ± 0.1 GtC yr⁻¹, SOCEAN was 2.6 ± 0.5 GtC yr⁻¹, and SLAND was 3.0 ± 0.8 GtC yr⁻¹. For the year 2014 alone,



EFF grew to $9.8 \pm 0.5 \text{ GtC yr}^{-1}$, 0.6 % above 2013, continuing the growth trend in these emissions, albeit at a slower rate compared to the average growth of 2.2 % yr^{-1} that took place during 2005–2014. Also, for 2014, ELUC was $1.1 \pm 0.5 \text{ GtC yr}^{-1}$, GATM was $3.9 \pm 0.2 \text{ GtC yr}^{-1}$, SOCEAN was $2.9 \pm 0.5 \text{ GtC yr}^{-1}$, and SLAND was $4.1 \pm 0.9 \text{ GtC yr}^{-1}$. GATM was lower in 2014 compared to the past decade (2005–2014), reflecting a larger SLAND for that year. The global atmospheric CO_2 concentration reached $397.15 \pm 0.10 \text{ ppm}$ averaged over 2014. For 2015, preliminary data indicate that the growth in EFF will be near or slightly below zero, with a projection of -0.6 [range of -1.6 to $+0.5$] %, based on national emissions projections for China and the USA, and projections of gross domestic product corrected for recent changes in the carbon intensity of the global economy for the rest of the world. From this projection of EFF and assumed constant ELUC for 2015, cumulative emissions of CO_2 will reach about $555 \pm 55 \text{ GtC}$ ($2035 \pm 205 \text{ GtCO}_2$) for 1870–2015, about 75 % from EFF and 25 % from ELUC. This living data update documents changes in the methods and data sets used in this new carbon budget compared with previous publications of this data set (Le Quéré et al., 2015, 2014, 2013). All observations presented here can be downloaded from the Carbon Dioxide Information Analysis Center (doi:10.3334/CDIAC/GCP_2015).

Global carbon budget 2016. Le Quéré C, Andrew RM, Canadell JG, Sitch S, Korsbakken, et al. (2016). *Earth System Science Data*, 8(2): 605-649.
<http://dx.doi.org/10.5194/essd-8-605-2016>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Accurate assessment of anthropogenic carbon dioxide (CO_2) emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere – the “global carbon budget” – is important to better understand the global carbon cycle, support the development of climate policies, and project future climate change. Here we describe data sets and methodology to quantify all major components of the global carbon budget, including their uncertainties, based on the combination of a range of data, algorithms, statistics, and model estimates and their interpretation by a broad scientific community. We discuss changes compared to previous estimates and consistency within and among components, alongside methodology and data limitations. CO_2 emissions from fossil fuels and industry (EFF) are based on energy statistics and cement production data, respectively, while emissions from land-use change (ELUC), mainly deforestation, are based on combined evidence from land-cover change data, fire activity associated with deforestation, and models. The global atmospheric CO_2 concentration is measured directly and its rate of growth (GATM) is computed from the annual changes in concentration. The mean ocean CO_2 sink (SOCEAN) is based on observations from the 1990s, while the annual anomalies and trends are estimated with ocean models. The variability in SOCEAN is evaluated with data products based on surveys of ocean CO_2 measurements. The global residual terrestrial CO_2 sink (SLAND) is estimated by the difference of the other terms of the global carbon budget and compared to results of independent dynamic global vegetation models. We compare the



mean land and ocean fluxes and their variability to estimates from three atmospheric inverse methods for three broad latitude bands. All uncertainties are reported as $\pm 1\sigma$, reflecting the current capacity to characterise the annual estimates of each component of the global carbon budget. For the last decade available (2006–2015), EFF was $9.3 \pm 0.5 \text{ GtC yr}^{-1}$, ELUC $1.0 \pm 0.5 \text{ GtC yr}^{-1}$, GATM $4.5 \pm 0.1 \text{ GtC yr}^{-1}$, SOCEAN $2.6 \pm 0.5 \text{ GtC yr}^{-1}$, and SLAND $3.1 \pm 0.9 \text{ GtC yr}^{-1}$. For year 2015 alone, the growth in EFF was approximately zero and emissions remained at $9.9 \pm 0.5 \text{ GtC yr}^{-1}$, showing a slowdown in growth of these emissions compared to the average growth of $1.8 \% \text{ yr}^{-1}$ that took place during 2006–2015. Also, for 2015, ELUC was $1.3 \pm 0.5 \text{ GtC yr}^{-1}$, GATM was $6.3 \pm 0.2 \text{ GtC yr}^{-1}$, SOCEAN was $3.0 \pm 0.5 \text{ GtC yr}^{-1}$, and SLAND was $1.9 \pm 0.9 \text{ GtC yr}^{-1}$. GATM was higher in 2015 compared to the past decade (2006–2015), reflecting a smaller SLAND for that year. The global atmospheric CO_2 concentration reached $399.4 \pm 0.1 \text{ ppm}$ averaged over 2015. For 2016, preliminary data indicate the continuation of low growth in EFF with $+0.2 \%$ (range of -1.0 to $+1.8 \%$) based on national emissions projections for China and USA, and projections of gross domestic product corrected for recent changes in the carbon intensity of the economy for the rest of the world. In spite of the low growth of EFF in 2016, the growth rate in atmospheric CO_2 concentration is expected to be relatively high because of the persistence of the smaller residual terrestrial sink (SLAND) in response to El Niño conditions of 2015–2016. From this projection of EFF and assumed constant ELUC for 2016, cumulative emissions of CO_2 will reach $565 \pm 55 \text{ GtC}$ ($2075 \pm 205 \text{ GtCO}_2$) for 1870–2016, about 75 % from EFF and 25 % from ELUC. This living data update documents changes in the methods and data sets used in this new carbon budget compared with previous publications of this data set (Le Quéré et al., 2015b, a, 2014, 2013). All observations presented here can be downloaded from the Carbon Dioxide Information Analysis Center (doi:10.3334/CDIAC/GCP_2016).

Global carbon budget 2017 Le Quéré C, Andrew RM, Friedlingstein P, Stich S, Pongratz J, et al. (2018). *Earth System Science Data*, **10**: 405-448.
<http://dx.doi.org/10.5194/essd-10-405-2018>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Accurate assessment of anthropogenic carbon dioxide (CO_2) emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere – the global carbon budget – is important to better understand the global carbon cycle, support the development of climate policies, and project future climate change. Here we describe data sets and methodology to quantify the five major components of the global carbon budget and their uncertainties. CO_2 emissions from fossil fuels and industry (E_{FF}) are based on energy statistics and cement production data, respectively, while emissions from land-use change (E_{LUC}), mainly deforestation, are based on land-cover change data and bookkeeping models. The global atmospheric CO_2 concentration is measured directly and its rate of growth (G_{ATM}) is computed from the annual changes in concentration. The ocean CO_2 sink (S_{OCEAN}) and terrestrial CO_2 sink (S_{LAND}) are



estimated with global process models constrained by observations. The resulting carbon budget imbalance (B_{IM}), the difference between the estimated total emissions and the estimated changes in the atmosphere, ocean, and terrestrial biosphere, is a measure of imperfect data and understanding of the contemporary carbon cycle. All uncertainties are reported as $\pm 1\sigma$. For the last decade available (2007–2016), E_{FF} was $9.4 \pm 0.5 \text{ GtC yr}^{-1}$, E_{LUC} $1.3 \pm 0.7 \text{ GtC yr}^{-1}$, G_{ATM} $4.7 \pm 0.1 \text{ GtC yr}^{-1}$, S_{OCEAN} $2.4 \pm 0.5 \text{ GtC yr}^{-1}$, and S_{LAND} $3.0 \pm 0.8 \text{ GtC yr}^{-1}$, with a budget imbalance B_{IM} of 0.6 GtC yr^{-1} indicating overestimated emissions and/or underestimated sinks. For year 2016 alone, the growth in E_{FF} was approximately zero and emissions remained at $9.9 \pm 0.5 \text{ GtC yr}^{-1}$. Also for 2016, E_{LUC} was $1.3 \pm 0.7 \text{ GtC yr}^{-1}$, G_{ATM} was $6.1 \pm 0.2 \text{ GtC yr}^{-1}$, S_{OCEAN} was $2.6 \pm 0.5 \text{ GtC yr}^{-1}$, and S_{LAND} was $2.7 \pm 1.0 \text{ GtC yr}^{-1}$, with a small B_{IM} of -0.3 GtC . G_{ATM} continued to be higher in 2016 compared to the past decade (2007–2016), reflecting in part the high fossil emissions and the small S_{LAND} consistent with El Niño conditions. The global atmospheric CO_2 concentration reached $402.8 \pm 0.1 \text{ ppm}$ averaged over 2016. For 2017, preliminary data for the first 6–9 months indicate a renewed growth in E_{FF} of $+2.0 \%$ (range of 0.8 to 3.0 %) based on national emissions projections for China, USA, and India, and projections of gross domestic product (GDP) corrected for recent changes in the carbon intensity of the economy for the rest of the world. This living data update documents changes in the methods and data sets used in this new global carbon budget compared with previous publications of this data set (Le Quéré et al., 2016, 2015b, a, 2014, 2013). All results presented here can be downloaded from <https://doi.org/10.18160/GCP-2017> (GCP, 2017).

Forests and carbon cycling

Forests are an important component of the global carbon cycle. They withdraw carbon from the atmosphere through photosynthesis and release it to the atmosphere through both plant and microbial respiration. Disturbances such as “stand-replacing” fires (i.e., those that kill all or most of the tree canopy) can release large amounts of CO_2 from forests. Humans affect forest carbon dynamics indirectly by altering natural fire patterns, increasing atmospheric CO_2 and nitrogen deposition, and changing global and regional climate.

Aboveground live carbon stock changes of California wildland ecosystems, 2001- 010. Gonzalez P, Battles JJ, Collins BM, Robards T, and Saah DS (2015). *Forest Ecology and Management*, **348**: 68-77. <http://dx.doi.org/10.1016/j.foreco.2015.03.040>

Geographic Location: California

Type of Reference: Research Paper

Abstract: The balance between ecosystem emissions of carbon to the atmosphere and removals from the atmosphere indicates whether ecosystems are exacerbating or reducing climate change. Forest ecosystems in the State of California, USA, contain carbon that reaches the highest densities (mass per unit area) in the world, but it has



been unresolved whether California ecosystems currently comprise a net sink or source of carbon. The California Global Warming Solutions Act of 2006 established greenhouse gas reduction targets for fossil fuel-burning sectors and ecosystems, underscoring the importance of tracking ecosystem carbon. Here, we conduct statewide spatial inventories of the aboveground live carbon stocks of forests and other terrestrial ecosystems of California, excluding agricultural and urban areas. We analyzed biomass data from field measurements of the Forest Inventory and Analysis program, published biomass information and remote sensing data on non-forest vegetation, and spatial distributions of vegetation types, height, and fractional cover derived by the Landfire program from Landsat remote sensing at 30 meter (m) spatial resolution. We conducted Monte Carlo analyses of the uncertainty of carbon stock change estimates from errors in tree biomass estimates, remote sensing, and estimates of the carbon fraction of biomass. The carbon stock in aboveground biomass was 850 ± 230 Teragrams (Tg) (mean \pm 95% confidence interval) in 2010. We found a net aboveground live carbon stock change of -69 ± 15 Tg from 2001 to 2010, a rate of change of $-0.8 \pm 0.2\%$ y^{-1} . Due to slow decay of some dead wood, all of the live carbon stock change does not immediately generate emissions. Wildfires on 6% of the state analysis area produced two-thirds of the live carbon stock loss. This suggests that increased tree densities from a century of fire suppression have allowed the accumulation of fuel for carbon losses in recent wildfires. Remote sensing errors in vegetation classification accounted for most of the uncertainty in the carbon stock change estimates. Improvements are also needed to track spatial patterns of growth and dead wood. Our results establish the beginning of a time series for the state greenhouse gas inventory and provide information on the role of forest conservation and management in California in mitigating global climate change.

Biophysical controls on carbon and water vapor fluxes across a grassland climatic gradient in the United States. Wagle P, Xiao X, Scott RL, Kolb TE, Cook DR, et al. (2015). *Agricultural and Forest Meteorology*, **214-215**: 293-305.
<http://dx.doi.org/10.1016/j.agrformet.2015.08.265>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: Understanding of the underlying causes of spatial variation in exchange of carbon and water vapor fluxes between grasslands and the atmosphere is crucial for accurate estimates of regional and global carbon and water budgets, and for predicting the impact of climate change on biosphere–atmosphere feedbacks of grasslands. We used ground-based eddy flux and meteorological data, and the Moderate Resolution Imaging Spectroradiometer (MODIS) enhanced vegetation index (EVI) from 12 grasslands across the United States to examine the spatial variability in carbon and water vapor fluxes and to evaluate the biophysical controls on the spatial patterns of fluxes. Precipitation was strongly associated with spatial and temporal variability in carbon and water vapor fluxes and vegetation productivity. Grasslands with annual average precipitation <600 millimeters (mm) generally had neutral annual carbon



balance or emitted small amount of carbon to the atmosphere. Despite strong coupling between gross primary production (GPP) and evapotranspiration (ET) across study sites, GPP showed larger spatial variation than ET, and EVI had a greater effect on GPP than on ET. Consequently, large spatial variation in ecosystem water use efficiency (EWUE = annual GPP/ET; varying from 0.67 ± 0.55 to 2.52 ± 0.52 g C mm⁻¹ ET) was observed. Greater reduction in GPP than ET at high air temperature and vapor pressure deficit caused a reduction in EWUE in dry years, indicating a response which is opposite than what has been reported for forests. Our results show that spatial and temporal variations in ecosystem carbon uptake, ET, and water use efficiency of grasslands were strongly associated with canopy greenness and coverage, as indicated by EVI.

Warm spring reduced carbon cycle impact of the 2012 US summer drought. Wolf S, Keenan TF, Fisher JB, Baldocchi D, Desai A, et al. (2016). *Proceedings of the National Academy of Sciences*, **113**(21): 201519620.
<http://dx.doi.org/10.1073/pnas.1519620113>

Geographic Location: United States
Type of Reference: Research Paper

Abstract: The global terrestrial carbon sink offsets one-third of the world's fossil fuel emissions, but the strength of this sink is highly sensitive to large-scale extreme events. In 2012, the contiguous United States experienced exceptionally warm temperatures and the most severe drought since the Dust Bowl era of the 1930s, resulting in substantial economic damage. It is crucial to understand the dynamics of such events because warmer temperatures and a higher prevalence of drought are projected in a changing climate. Here, we combine an extensive network of direct ecosystem flux measurements with satellite remote sensing and atmospheric inverse modeling to quantify the impact of the warmer spring and summer drought on biosphere-atmosphere carbon and water exchange in 2012. We consistently find that earlier vegetation activity increased spring carbon uptake and compensated for the reduced uptake during the summer drought, which mitigated the impact on net annual carbon uptake. The early phenological development in the Eastern Temperate Forests played a major role for the continental-scale carbon balance in 2012. The warm spring also depleted soil water resources earlier, and thus exacerbated water limitations during summer. Our results show that the detrimental effects of severe summer drought on ecosystem carbon storage can be mitigated by warming-induced increases in spring carbon uptake. However, the results also suggest that the positive carbon cycle effect of warm spring enhances water limitations and can increase summer heating through biosphere-atmosphere feedbacks.



Ocean acidification

As atmospheric concentrations of CO₂ increase, so do levels in the ocean. The ocean absorbs approximately 30 percent of the CO₂ released into the atmosphere by human activities every year, changing the chemistry of sea water — a process known as ocean acidification. This process has significantly slowed the CO₂ buildup in the atmosphere and reduced some of its impacts on global warming. The ocean's role as a sink for CO₂ comes at a cost to marine life. Acidification presents a significant threat to marine ecosystems, particularly those that form shells and exoskeletons such as mollusks and coral.

A time-series view of changing ocean chemistry due to ocean uptake of anthropogenic CO₂ and ocean acidification. Bates N, Astor Y, Church M, Currie K, Dore J, et al. (2014). *Oceanography*, **27**: 126-141.
<http://dx.doi.org/10.5670/oceanog.2014.16>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Sustained observations provide critically needed data and understanding not only about ocean warming and water cycle reorganization (e.g., salinity changes), ocean eutrophication, and ocean deoxygenation, but also about changes in ocean chemistry. As an example of changes in the global ocean carbon cycle, consistent changes in surface seawater CO₂-carbonate chemistry are documented by seven independent CO₂ time series that provide sustained ocean observations collected for periods from 15 to 30 years: (1) Iceland Sea, (2) Irminger Sea, (3) Bermuda Atlantic Time-series Study (BATS), (4) European Station for Time series in the Ocean at the Canary Islands (ESTOC), (5) CARbon Retention In A Colored Ocean sites in the North Atlantic (CARIACO), (6) Hawaii Ocean Time-series (HOT), and (7) Munida in the Pacific Ocean. These ocean time-series sites exhibit very consistent changes in surface ocean chemistry that reflect the impact of uptake of anthropogenic CO₂ and ocean acidification. The article discusses the long-term changes in dissolved inorganic carbon (DIC), salinity-normalized DIC, and surface seawater pCO₂ (partial pressure of CO₂) due to the uptake of anthropogenic CO₂ and its impact on the ocean's buffering capacity. In addition, we evaluate changes in seawater chemistry that are due to ocean acidification and its impact on pH and saturation states for biogenic calcium carbonate minerals.



Characterizing the natural system: Toward sustained, integrated coastal ocean acidification observing networks to facilitate resource management and decision support. Alin SR, Brainard RE, Price NN, Newton JA, Cohen A, Pterson WT, et al. (2015). *Oceanography*, **28**(2): 92–107. <http://dx.doi.org/10.5670/oceanog.2015.34>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Coastal ocean ecosystems have always served human populations—they provide food security, livelihoods, coastal protection, and defense. Ocean acidification is a global threat to these ecosystem services, particularly when other local and regional stressors combine with it to jeopardize coastal health. Monitoring efforts call for a coordinated global approach toward sustained, integrated coastal ocean health observing networks to address the region-specific mix of factors while also adhering to global ocean acidification observing network principles to facilitate comparison among regions for increased utility and understanding. Here, we generalize guidelines for scoping and designing regional coastal ocean acidification observing networks and provide examples of existing efforts. While challenging in the early stages of coordinating the design and prioritizing the implementation of these observing networks, it is essential to actively engage all of the relevant stakeholder groups from the outset, including private industries, public agencies, regulatory bodies, decision makers, and the general public. The long-term sustainability of these critical observing networks will rely on leveraging of resources and the strength of partnerships across the consortium of stakeholders and those implementing coastal ocean health observing networks.

Introduction to this special issue on ocean acidification: The pathway from science to policy. Mathis JT, Cooley SR, Yates KK, and Williamson P (2015). *Oceanography*, **28**(2): 10–15. <http://dx.doi.org/10.5670/oceanog.2015.26>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Ocean acidification (OA) is a progressive decrease in the pH of seawater over decades, caused primarily by uptake of excess atmospheric CO₂ and accompanied by changes in seawater carbonate chemistry. Scientific studies designed to examine the effects of anthropogenic carbon dioxide (CO₂) emissions on global carbon fluxes have also led to the detection of OA. During the last decade, this phenomenon has surged to the attention of not only scientists but also policymakers and the public. OA chemistry is well understood and follows first principles of acid-base chemistry. Today, total anthropogenic release of CO₂ exceeds nine petagrams of carbon annually, with ~85% coming directly from industrial sources and ~15% from changes in land use. The three major sinks for this CO₂ are: ~46% of CO₂ emitted remains in the atmosphere, ~29% is absorbed by the terrestrial biosphere, and the ocean absorbs the remaining ~26%, resulting in OA. Since the Industrial Revolution, global average surface ocean pH has dropped 0.1 unit (about a 30% increase in



acidity), and it is expected to drop another 0.3 to 0.4 units by 2100 (100-150% increase in acidity) if CO₂ emissions continue in a business-as-usual scenario. Some areas of the ocean, such as coastal regions, upwelling zones, and polar seas, may be subjected to much greater chemical perturbations from OA than indicated by such globally averaged values).

Chemical and biological impacts of ocean acidification along the west coast of North America. Feely RA, Alin SR, Carter B, Bednaršek N, Hales B, Chan F, et al. (2016). *Estuarine, Coastal and Shelf Science*, **183**(Part A): 260-270.
<http://dx.doi.org/10.1016/j.ecss.2016.08.043>

Geographic Location: Pacific Ocean/West Coast

Type of Reference: Research Paper

Abstract: The continental shelf region off the west coast of North America is seasonally exposed to water with a low aragonite saturation state by coastal upwelling of CO₂-rich waters. To date, the spatial and temporal distribution of anthropogenic CO₂ (C_{anth}) within the CO₂-rich waters is largely unknown. Here we adapt the multiple linear regression approach to utilize the GO-SHIP Repeat Hydrography data from the northeast Pacific to establish an annually updated relationship between C_{anth} and potential density. This relationship was then used with the NOAA Ocean Acidification Program West Coast Ocean Acidification (WCOA) cruise data sets from 2007, 2011, 2012, and 2013 to determine the spatial variations of C_{anth} in the upwelled water. Our results show large spatial differences in C_{anth} in surface waters along the coast, with the lowest values (37–55 μmol kg⁻¹) in strong upwelling regions off southern Oregon and northern California and higher values (51–63 μmol kg⁻¹) to the north and south of this region. Coastal dissolved inorganic carbon concentrations are also elevated due to a natural remineralized component (C_{bio}), which represents carbon accumulated through net respiration in the seawater that has not yet degassed to the atmosphere. Average surface C_{anth} is almost twice the surface remineralized component. In contrast, C_{anth} is only about one third and one fifth of the remineralized component at 50 m and 100 m depth, respectively. Uptake of C_{anth} has caused the aragonite saturation horizon to shoal by approximately 30–50 m since the preindustrial period so that undersaturated waters are well within the regions of the continental shelf that affect the shell dissolution of living pteropods. Our data show that the most severe biological impacts occur in the nearshore waters, where corrosive waters are closest to the surface. Since the pre-industrial times, pteropod shell dissolution has, on average, increased approximately 19–26% in both nearshore and offshore waters.



Persistent spatial structuring of coastal ocean acidification in the California Current System. Chan F, Barth JA, Blanchette CA, Byrne RH, Chavez F, et al. (2017). *Scientific Reports*, 7: 2526. <http://dx.doi.org/10.1038/s41598-017-02777-y>

Geographic Location: California Current System/Pacific Ocean

Type of Reference: Research Paper

Abstract: The near-term progression of ocean acidification (OA) is projected to bring about sharp changes in the chemistry of coastal upwelling ecosystems. The distribution of OA exposure across these early-impact systems, however, is highly uncertain and limits our understanding of whether and how spatial management actions can be deployed to ameliorate future impacts. Through a novel coastal OA observing network, we have uncovered a remarkably persistent spatial mosaic in the penetration of acidified waters into ecologically-important nearshore habitats across 1,000 km of the California Current Large Marine Ecosystem. In the most severe exposure hotspots, suboptimal conditions for calcifying organisms encompassed up to 56% of the summer season, and were accompanied by some of the lowest and most variable pH environments known for the surface ocean. Persistent refuge areas were also found, highlighting new opportunities for local adaptation to address the global challenge of OA in productive coastal systems.

Land use

Human activities can affect regional climate through land use changes, such as deforestation, irrigation, and urbanization. Modifications to land surfaces affect the amount of solar radiation that is reflected by such surfaces back into space. For example, conversion of undeveloped land to urbanized areas with dark pavements increases warming, while white roofs or reflective building materials reduce warming. In addition to affecting the reflection or absorption of radiative energy, land use changes can impact surface temperatures as a result of altered surface roughness, latent heat flux (the transfer of heat from surface waters to the atmosphere), river runoff and irrigation.

Quantifying the effect of urbanization on U.S. Historical Climatology Network temperature records. Hausfather, Z, Menne MJ, Williams CN, Masters T, Broberg R, and Jones D (2013). *Journal of Geophysical Research: Atmospheres*, 118(2): 481-494. <http://dx.doi.org/10.1029/2012JD018509>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: An assessment quantifying the impact of urbanization on temperature trends from the U.S. Historical Climatology Network (USHCN) is described. Stations were first classified as urban and nonurban (rural) using four different proxy measures of urbanity.



Trends from the two station types were then compared using a pairing method that controls for differences in instrument type and via spatial gridding to account for the uneven distribution of stations. The comparisons reveal systematic differences between the raw (unadjusted) urban and rural temperature trends throughout the USHCN period of record according to all four urban classifications. According to these classifications, urbanization accounts for 14–21% of the rise in unadjusted minimum temperatures since 1895 and 6–9% since 1960. The USHCN version 2 homogenization process effectively removes this urban signal such that it becomes insignificant during the last 50–80 years. In contrast, prior to 1930, only about half of the urban signal is removed. Accordingly, the National Aeronautics and Space Administration Goddard Institute for Space Studies urban-correction procedure has essentially no impact on USHCN version 2 trends since 1930, but effectively removes the residual urban-rural temperature trend differences for years before 1930 according to all four urban proxy classifications. Finally, an evaluation of the homogenization of USHCN temperature series using subsets of rural-only and urban-only reference series from the larger U.S. Cooperative Observer (Coop) Network suggests that the composition of Coop stations surrounding USHCN stations is sufficiently “rural” to limit the aliasing of urban heat island signals onto USHCN version 2 temperature trends during homogenization.

Combined impacts of land cover changes and large-scale forcing on Southern California summer daily maximum temperatures. Sequera P, González JE, McDonald K, Bornstein R, and Comarazamy D (2015). *Journal of Geophysical Research: Atmospheres*, **120**(18): 9208-9219. <http://dx.doi.org/10.1002/2015JD023536>

Geographic Location: Southern California

Type of Reference: Research Paper

Abstract: California near-surface air temperatures are influenced by large-scale, regional and local factors. In that sense, a numerical model experiment was carried out to analyze the contribution of large-scale (changes in atmospheric and oceanic conditions) and regional (increased urbanization) factors on the observed California South Coast Air Basin regional summer daily maximum temperature warming pattern from 1950 to 2013. The simulations were performed with past (1950–1954) and present (2009–2013) land cover and climate conditions. The past land cover was derived from historical digital maps, and the present land cover was updated with high-resolution airborne remote sensing data. Results show that both factors contribute to the total change in daily maximum temperatures. Changes due to large-scale climate conditions dominate in coastal (due to warming sea surface temperatures) and nonurban regions, while changes due to urbanization have an impact mainly in urban areas, especially inland where large-scale warming weakens. Increased urbanization has also reduced sea-breeze intensity due to changes in surface roughness. The model was able to reproduce the regional observed warming pattern, as it incorporates urban heat island effects, otherwise underestimated by large-scale climate change only.



The terrestrial biosphere as a net source of greenhouse gases to the atmosphere.

Tian H, Lu C, Ciais P, Michalak AM, Canadell J, et al. (2016). *Nature*, **531**(7593): 225-228. <http://dx.doi.org/10.1038/nature16946>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: The terrestrial biosphere can release or absorb the greenhouse gases, carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), and therefore has an important role in regulating atmospheric composition and climate. Anthropogenic activities such as land-use change, agriculture and waste management have altered terrestrial biogenic greenhouse gas fluxes, and the resulting increases in methane and nitrous oxide emissions in particular can contribute to climate change. The terrestrial biogenic fluxes of individual greenhouse gases have been studied extensively, but the net biogenic greenhouse gas balance resulting from anthropogenic activities and its effect on the climate system remains uncertain. Here we use bottom-up (inventory, statistical extrapolation of local flux measurements, and process-based modelling) and top-down (atmospheric inversions) approaches to quantify the global net biogenic greenhouse gas balance between 1981 and 2010 resulting from anthropogenic activities and its effect on the climate system. We find that the cumulative warming capacity of concurrent biogenic methane and nitrous oxide emissions is a factor of about two larger than the cooling effect resulting from the global land carbon dioxide uptake from 2001 to 2010. This results in a net positive cumulative impact of the three greenhouse gases on the planetary energy budget, with a best estimate (in petagrams of CO₂ equivalent per year) of 3.9 ± 3.8 (top down) and 5.4 ± 4.8 (bottom up) based on the GWP100 metric (global warming potential on a 100-year time horizon). Our findings suggest that a reduction in agricultural methane and nitrous oxide emissions, particularly in Southern Asia, may help mitigate climate change.

Urbanization causes increased cloud base height and decreased fog in coastal Southern California. Williams AP, Schwartz RE, Iacobellis S, Seager R, Cook BI, et al. (2016). *Geophysical Research Letters*, **42**(5): 1527-1536.

<http://dx.doi.org/10.1002/2015GL063266>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Subtropical marine stratus clouds regulate coastal and global climate, but future trends in these clouds are uncertain. In coastal Southern California (CSCA), interannual variations in summer stratus cloud occurrence are spatially coherent across 24 airfields and dictated by positive relationships with stability above the marine boundary layer (MBL) and MBL height. Trends, however, have been spatially variable since records began in the mid-1900s due to differences in nighttime warming. Among CSCA airfields, differences in nighttime warming, but not daytime warming, are strongly and positively related to fraction of nearby urban cover, consistent with an urban heat



island effect. Nighttime warming raises the near-surface dew point depression, which lifts the altitude of condensation and cloud base height, thereby reducing fog frequency. Continued urban warming, rising cloud base heights, and associated effects on energy and water balance would profoundly impact ecological and human systems in highly populated and ecologically diverse CSCA.

Local- and landscape-scale land cover affects microclimate and water use in urban gardens. Lin BB, Egerer MH, Liere H, Jha S, Bichier P, and Philpott SM (2018). *Science of the Total Environment*, **610-611**: 570-575.
<http://dx.doi.org/10.1016/j.scitotenv.2017.08.091>

Geographic Location: California's Central Coast
Type of Reference: Research Paper

Abstract: Urban gardens in Central California are highly vulnerable to the effects of climate change, experiencing both extended high heat periods as well as water restrictions because of severe drought conditions. This puts these critical community-based food production systems at risk as California is expected to experience increasing weather extremes. In agricultural systems, increased vegetation complexity, such as greater structure or biodiversity, can increase the resilience of food production systems from climate fluctuations. We test this theory in 15 urban gardens across California's Central Coast. Local- and landscape-scale measures of ground, vegetation, and land cover were collected in and around each garden, while climate loggers recorded temperatures in each garden in 30 min increments. Multivariate analyses, using county as a random factor, show that both local- and landscape-scale factors were important. All factors were significant predictors of mean temperature. Tallest vegetation, tree/shrub species richness, grass cover, mulch cover, and landscape level agricultural cover were cooling factors; in contrast, garden size, garden age, rock cover, herbaceous species richness, and landscape level urban cover were warming factors. Results were similar for the maximum temperature analysis except that agriculture land cover and herbaceous species richness were not significant predictors of maximum temperature. Analysis of gardener watering behavior to observed temperatures shows that garden microclimate was significantly related to the number of minutes watered as well as the number of liters of water used per watering event. Thus gardeners seem to respond to garden microclimate in their watering behavior even though this behavior is most probably motivated by a range of other factors such as water regulations and time availability. This research shows that local management of ground cover and vegetation can reduce mean and maximum temperatures in gardens, and the reduced temperatures may influence watering behavior of gardeners.



Changes in Climate

The atmosphere, land surface, glaciers, ice and other frozen surfaces, oceans and other bodies of water and living things make up the complex, interactive climate system. Climate, which is generally defined as “average weather”, is usually described in terms of the mean and variability of temperature, precipitation and wind over a period of time.

Temperature

Temperature is a basic physical factor that affects many natural processes and human activities. It is influenced by local topography, proximity to the ocean, and global and regional atmospheric and oceanic circulations. Climate patterns can vary widely from year to year and from decade to decade, in accordance with large-scale circulation changes around the Earth. The increase in the concentration of CO₂ and other greenhouse gases in the Earth’s atmosphere since the Industrial Revolution in the mid-1700s has been a principal factor causing warming observed world-wide. A slowdown in the global rate of warming was observed from 1998 to 2012. Since then, temperatures have steadily risen. Recent studies presented in this bibliography looked at possible explanations for this “global warming hiatus”, as well as regional trends in warming.

An apparent hiatus in global warming? Trenberth KE and Fasullo JT (2013). *Earth’s Future*, 1(1): 19-32. <http://dx.doi.org/10.1002/2013EF000165>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Global warming first became evident beyond the bounds of natural variability in the 1970s, but increases in global mean surface temperatures have stalled in the 2000s. Increases in atmospheric greenhouse gases, notably carbon dioxide, create an energy imbalance at the top-of-atmosphere (TOA) even as the planet warms to adjust to this imbalance, which is estimated to be 0.5–1 W square meters (m⁻²) over the 2000s. Annual global fluctuations in TOA energy of up to 0.2 W m⁻² occur from natural variations in clouds, aerosols, and changes in the Sun. At times of major volcanic eruptions the effects can be much larger. Yet global mean surface temperatures fluctuate much more than these can account for. An energy imbalance is manifested not just as surface atmospheric or ground warming but also as melting sea and land ice, and heating of the oceans. More than 90% of the heat goes into the oceans and, with melting land ice, causes sea level to rise. For the past decade, more than 30% of the heat has apparently penetrated below 700 m depth that is traceable to changes in surface winds mainly over the Pacific in association with a switch to a negative phase of the Pacific Decadal Oscillation (PDO) in 1999. Surface warming was much more in evidence during the 1976–1998 positive phase of the PDO, suggesting that natural decadal variability modulates the rate of change of global surface temperatures while



sea-level rise is more relentless. Global warming has not stopped; it is merely manifested in different ways.

Interannual variability in associations between seasonal climate, weather, and extremes: Wintertime temperature over the Southwestern United States.

Guirguis K, Gershunov A and Cayan DR (2015). *Environmental Research Letters*, 10(12): 124023. <http://dx.doi.org/10.1088/1748-9326/10/12/124023>

Geographic Location: Southwestern United States

Type of Reference: Research Paper

Abstract: Temperature variability in the Southwest US is investigated using skew-normal probability distribution functions (SN PDFs) fitted to observed wintertime daily maximum temperature records. These PDFs vary significantly between years, with important geographical differences in the relationship between the central tendency and tails, revealing differing linkages between weather and climate. The warmest and coldest extremes do not necessarily follow the distribution center. In some regions one tail of the distribution shows more variability than does the other. For example, in California the cold tail is more variable while the warm tail remains relatively stable, so warm years are associated with fewer cold extremes but not necessarily more warm extremes. The opposite relationship is seen in the Great Plains. Changes in temperature PDFs are conditioned by different phases of El Niño-La Niña (ENSO) and the Pacific decadal oscillation (PDO). In the Southern Great Plains, La Niña and/or negative PDO are associated with generally warmer conditions. However, in terms of extremes, while the warm tails become thicker and longer, the cool tails are not impacted—extremely warm days become more frequent but extremely cool days are not less frequent. In contrast, in coastal California, La Niña or negative PDO bring generally cooler conditions with more/stronger cold extremes but the warm extreme probability is not significantly affected. These results could have implications for global warming. If a rigid shift of the whole range occurs, then warm years are not necessarily a good analogue for a warmer climate. If global warming instead brings regional changes more aligned with a preferred state of dominant climate variability modes, then we may see asymmetric changes in the tails of local temperature PDFs.

Decadal modulation of global surface temperature by internal climate variability.

Dai A, Fyfe JC, Xie S-P and Dai X (2015). *Nature Climate Change*, 5: 555-550. <http://dx.doi.org/10.1038/nclimate2605>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Despite a steady increase in atmospheric greenhouse gases (GHGs), global-mean surface temperature (T) has shown no discernible warming since about 2000, in



sharp contrast to model simulations, which on average project strong warming. The recent slowdown in observed surface warming has been attributed to decadal cooling in the tropical Pacific, intensifying trade winds, changes in El Niño activity, increasing volcanic activity and decreasing solar irradiance. Earlier periods of arrested warming have been observed but received much less attention than the recent period, and their causes are poorly understood. Here we analyse observed and model-simulated global T fields to quantify the contributions of internal climate variability (ICV) to decadal changes in global-mean T since 1920. We show that the Interdecadal Pacific Oscillation (IPO) has been associated with large T anomalies over both ocean and land. Combined with another leading mode of ICV, the IPO explains most of the difference between observed and model-simulated rates of decadal change in global-mean T since 1920, and particularly over the so-called ‘hiatus’ period since about 2000. We conclude that ICV, mainly through the IPO, was largely responsible for the recent slowdown, as well as for earlier slowdowns and accelerations in global-mean T since 1920, with preferred spatial patterns different from those associated with GHG-induced warming or aerosol-induced cooling. Recent history suggests that the IPO could reverse course and lead to accelerated global warming in the coming decades.

Possible artifacts of data biases in the recent global surface warming hiatus. Karl TR, Arguez A, Huang B, Lawrimore J, McMahon J, et al. (2015). *Science*, **348**(6242): 1469--1472. <http://dx.doi.org/10.1126/science.aaa5632>

Geographic Location: Global
Type of Reference: Research Paper

Abstract: Much study has been devoted to the possible causes of an apparent decrease in the upward trend of global surface temperatures since 1998, a phenomenon that has been dubbed the global warming “hiatus.” Here, we present an updated global surface temperature analysis that reveals that global trends are higher than those reported by the Intergovernmental Panel on Climate Change, especially in recent decades, and that the central estimate for the rate of warming during the first 15 years of the 21st century is at least as great as the last half of the 20th century. These results do not support the notion of a “slowdown” in the increase of global surface temperature.

The global warming hiatus: Slowdown or redistribution? Yan X-H, Boyer T, Trenberth K, Karl TR, Xie S-P, et al. (2016). *Earth's Future*, **4**(11): 472--482. <http://dx.doi.org/10.1002/2016EF000417>

Geographic Location: Global
Type of Reference: Review Article



Abstract: Global mean surface temperatures (GMST) exhibited a smaller rate of warming during 1998–2013, compared to the warming in the latter half of the 20th Century. Although, not a “true” hiatus in the strict definition of the word, this has been termed the “global warming hiatus” by IPCC (2013). There have been other periods that have also been defined as the “hiatus” depending on the analysis. There are a number of uncertainties and knowledge gaps regarding the “hiatus.” This report reviews these issues and also posits insights from a collective set of diverse information that helps us understand what we do and do not know. One salient insight is that the GMST phenomenon is a surface characteristic that does not represent a slowdown in warming of the climate system but rather is an energy redistribution within the oceans. Improved understanding of the ocean distribution and redistribution of heat will help better monitor Earth's energy budget and its consequences. A review of recent scientific publications on the “hiatus” shows the difficulty and complexities in pinpointing the oceanic sink of the “missing heat” from the atmosphere and the upper layer of the oceans, which defines the “hiatus.” Advances in “hiatus” research and outlooks (recommendations) are given in this report.

Reconciling divergent trends and millennial variations in Holocene temperatures. Marsicek J, Shuman BN, Bartlein PJ, Shafer SL, and Brewer S (2018). *Nature*, **554**: 92-96.

Geographic Location: North America and Europe
Type of Reference: Research Paper

Abstract: Cooling during most of the past two millennia has been widely recognized and has been inferred to be the dominant global temperature trend of the past 11,700 years (the Holocene epoch). However, long-term cooling has been difficult to reconcile with global forcing, and climate models consistently simulate long-term warming. The divergence between simulations and reconstructions emerges primarily for northern mid-latitudes, for which pronounced cooling has been inferred from marine and coastal records using multiple approaches. Here we show that temperatures reconstructed from sub-fossil pollen from 642 sites across North America and Europe closely match simulations, and that long-term warming, not cooling, defined the Holocene until around 2,000 years ago. The reconstructions indicate that evidence of long-term cooling was limited to North Atlantic records. Early Holocene temperatures on the continents were more than two degrees Celsius below those of the past two millennia, consistent with the simulated effects of remnant ice sheets in the climate model Community Climate System Model 3 (CCSM3). CCSM3 simulates increases in ‘growing degree days’—a measure of the accumulated warmth above five degrees Celsius per year—of more than 300 kelvin days over the Holocene, consistent with inferences from the pollen data. It also simulates a decrease in mean summer temperatures of more than two degrees Celsius, which correlates with reconstructed marine trends and highlights the potential importance of the different subseasonal sensitivities of the records. Despite the differing trends, pollen- and marine-based reconstructions are correlated at millennial-to-centennial scales, probably in response to



ice-sheet and meltwater dynamics, and to stochastic dynamics similar to the temperature variations produced by CCSM3. Although our results depend on a single source of palaeoclimatic data (pollen) and a single climate-model simulation, they reinforce the notion that climate models can adequately simulate climates for periods other than the present-day. They also demonstrate that amplified warming in recent decades increased temperatures above the mean of any century during the past 11,000 years.

Precipitation

A changing climate can directly influence the amount, intensity and frequency of snowfall, rainfall and other forms of precipitation. Large natural variability and strong geographic variations in these parameters are evident, and substantially affected by atmospheric circulation patterns such as the El Niño Southern Oscillation. Increased warming accelerates evaporation and increases the amount of water vapor in the atmosphere, resulting in certain areas getting wetter and others getting drier. Widespread increases in heavy precipitation events have occurred even in places where total amounts have decreased.

Atmospheric rivers as drought busters on the U.S. west coast. Dettinger MD (2013). *Journal of American Meteorology Society*, **14**: 1721-1732.
<https://doi.org/10.1175/JHM-D-13-02.1>

Geographic Location: West Coast of North America
Type of Reference: Research Paper

Abstract: Atmospheric rivers (ARs) have, in recent years, been recognized as the cause of the large majority of major floods in rivers all along the U.S. West Coast and as the source of 30%–50% of all precipitation in the same region. The present study surveys the frequency with which ARs have played a critical role as a common cause of the end of droughts on the West Coast. This question was based on the observation that, in most cases, droughts end abruptly as a result of the arrival of an especially wet month or, more exactly, a few very large storms. This observation is documented using both Palmer Drought Severity Index and 6-month Standardized Precipitation Index measures of drought occurrence for climate divisions across the conterminous United States from 1895 to 2010. When the individual storm sequences that contributed most to the wet months that broke historical West Coast droughts from 1950 to 2010 were evaluated, 33%–74% of droughts were broken by the arrival of landfalling AR storms. In the Pacific Northwest, 60%–74% of all persistent drought endings have been brought about by the arrival of AR storms. In California, about 33%–40% of all persistent



drought endings have been brought about by landfalling AR storms, with more localized low pressure systems responsible for many of the remaining drought breaks.

Trends in atmospheric patterns conducive to seasonal precipitation and temperature extremes in California. Swain DL, Horton DE, Singh D, and Diffenbaugh NS (2016). *Science Advances*, 2(4): e1501344.

Geographic Location: California

Type of Reference: Research Paper

Abstract: Recent evidence suggests that changes in atmospheric circulation have altered the probability of extreme climate events in the Northern Hemisphere. We investigate northeastern Pacific atmospheric circulation patterns that have historically (1949–2015) been associated with cool-season (October–May) precipitation and temperature extremes in California. We identify changes in occurrence of atmospheric circulation patterns by measuring the similarity of the cool-season atmospheric configuration that occurred in each year of the 1949–2015 period with the configuration that occurred during each of the five driest, wettest, warmest, and coolest years. Our analysis detects statistically significant changes in the occurrence of atmospheric patterns associated with seasonal precipitation and temperature extremes. We also find a robust increase in the magnitude and subseasonal persistence of the cool-season West Coast ridge, resulting in an amplification of the background state. Changes in both seasonal mean and extreme event configurations appear to be caused by a combination of spatially nonuniform thermal expansion of the atmosphere and reinforcing trends in the pattern of sea level pressure. In particular, both thermal expansion and sea level pressure trends contribute to a notable increase in anomalous northeastern Pacific ridging patterns similar to that observed during the 2012–2015 California drought. Collectively, our empirical findings suggest that the frequency of atmospheric conditions like those during California’s most severely dry and hot years has increased in recent decades, but not necessarily at the expense of patterns associated with extremely wet years.

Variability and trends in precipitation, temperature and drought indices in the state of California. He M and Guatam M (2016). *Hydrology*, 3(2): 14.
<http://dx.doi.org/10.3390/hydrology3020014>

Geographic Location: California

Type of Reference: Research Paper

Abstract: This study presents a comprehensive assessment of the variability and trends of the precipitation and temperature along with the trends in drought indices over the State of California. The non-parametric Mann–Kendall trend test is applied with a trend-free pre-whitening procedure in trend identification. A dataset containing 120-year



(water years 1896–2015) monthly precipitation, average temperature, maximum temperature, minimum temperature and the Palmer Index for seven climatic regions of the state is used for this purpose. The results confirm previous work indicating that no clear trends are observed in precipitation, while a distinct warming trend is evident in temperature over the state. New findings of this study include: (1) in general, the variability of annual, winter (December–February) and spring (March–May) precipitation shows an increasing tendency, implying intensified frequency of the occurrence of dry or wet extremes; (2) on the annual scale and in the summer, statewide meteorological, hydrological and agricultural drought indices all have decreasing trends, indicating the more frequent occurrence of drought events; and (3) among seven regions, the South Coast Drainage region generally has the most significant warming trend, as well as the most significant declining trends in drought indices. Overall, these findings are highly meaningful from both theoretical and practical perspectives, in the context of providing critical information in developing prediction models and guiding water resources management practices, respectively.

Historical and future relations between large storms and droughts in California.

Dettinger MD (2016). *San Francisco Estuary and Watershed Science*, **14**(2).

<http://dx.doi.org/10.15447/sfews.2016v14iss2art1>

Geographic Location: California

Type of Reference: Research Paper

Abstract: California precipitation varies more dramatically from year to year than elsewhere in the conterminous United States. This paper analyzes the extent to which contributions of the wettest days to overall precipitation dictate the state's precipitation seasonality and frequent multiyear periods of drought (as precipitation deficit) and plenty is analyzed, historically and in projections of future climates. The wettest 5% of wet days in California contribute about a third of precipitation but about two-thirds of the variance of water-year precipitation. Year-to-year fluctuations in precipitation strongly reflect year-to-year fluctuations of contributions from the largest storms, with the large-storm contributions explaining about twice as much precipitation fluctuation as do contributions from all remaining storms combined. This extreme dominance of large storms is largely unique to California within the United States. In climate-change projections, eight of ten climate models considered here yield increases in precipitation from the largest storms, and when the increases are large, total precipitation follows suit. All of the models project declines in contributions from the smaller storms and models projecting total-precipitation declines reflect this decline. Projected changes in variance of water-year precipitation reflect changes in variance of large-storm contributions. The disproportionately large overall contributions from California's largest storms, and their outsized year-to-year variability, ensure that the state's largest storms dictate the state's regimes of wet and dry spells, historically and in climate-change projections.



Hydroclimate Report Water Year 2015. California Department of Water Resources (2016). https://www.water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Files/a3037_Hydroclimate_report_v11.pdf

Geographic Location: California

Type of Reference: Report

Executive Summary: Water year 2015 added a fourth year to the ongoing drought in California, with observations indicative of a changing climate, including record warmth. The Water year ended with record high temperatures, and preceded a period of historically low precipitation that started in 2012. April snowpack measurements in 2014 tied the historic record low of 1977. Expectations of a developing El Niño event in the eastern tropical Pacific fueled notions that water year 2015 would be better. However, during the first two months of the water year, warm temperatures persisted and precipitation continued to fall short of expectations. The developing El Niño event stalled as California headed into the heart of its wet season.

In 2014, the snowpack level was 25% of its average on April 1. That mark was shattered on April 1, 2015 when snowpack amounted to a meager 5% of average. Satellite-imagery compares the Sierra Nevada snowpack near the end of March 2015 to the average conditions in water year 2011. This extreme low in snowpack exceeds end-of-century climate projections. When accompanied by the record warm temperatures experienced in the 2015 water year, there is conversation of California having shifted to a new climate “normal”.

Hydroclimate Report Water Year 2016. California Department of Water Resources (2017). https://www.water.ca.gov/LegacyFiles/climatechange/docs/2018/2016_HydroclimateReport.pdf

Geographic Location: California

Type of Reference: Report

Executive Summary: Water year 2016 ended up being different than expected, from a climate standpoint. Water year 2015 marked the 4th year of drought in California, ending with record high temperatures, record low precipitation, and a record low snowpack. Forecasts were for a strong, wet El Niño during water year 2016, with the potential to rival large flood producing events of 1983 and 1998, higher than average sea levels, increased wave action and potential damage along the coast, warmer than average temperatures, and above-average precipitation producing storms. As a result of the cooling of the tropical Pacific sea surface temperatures, and the decay of El Niño, only some of the anticipated impacts were realized, above-average precipitation and greater than average snowpack did not come to pass.



While statewide air temperatures averaged lower than the record setting 2015 water year they were still well above the long-term record, ranking water year 2016 warmest 117 of 121 since 1895. Precipitation was above normal in the Northern Sierra with the majority of precipitation falling in January and March. Precipitation in the Southern Sierra was on average with the long-term trend. Differences in Northern and Southern Sierra precipitation were due to the majority of Atmospheric River landfalls occurring in the north including the two strongest occurring in the first two weeks of March while only two Atmospheric Rivers made landfall south of Monterey Bay.

Statewide snowpack was 15 percent below average and impacted the April-July snowmelt with streamflow on the Sacramento and San Joaquin Rivers by 32 percent and 22 percent below average respectively. Water year type was classified as “Below Normal” for the Sacramento River system and “Dry” for the San Joaquin. Overall, water year 2016 was an improvement to the previous four years of drought conditions with enough precipitation to offset some of the large deficits in water storage reservoirs

Water Year 2017: What a Difference a Year Makes. California Department of Water Resources (2017).

<https://www.water.ca.gov/LegacyFiles/waterconditions/docs/2017/Water%20Year%202017.pdf>

Geographic Location: California

Type of Reference: Report

Abstract: Water year 2017 (October 1, 2016 to September 30, 2017) dramatically illustrated the variability in California's annual precipitation, ending the state's 5-year drought and coming in at second place for statewide runoff, behind the wettest year of 1983. Virtually all of the state experienced at least average precipitation, and key Sierra Nevada watersheds were much above average. Governor Brown lifted the proclamation of statewide drought emergency he issued in 2014, although the state-declared emergency remained in selected central California counties experiencing lingering drought impacts. Prior to 2017, California had experienced a decade of largely dry conditions. Eight of the ten preceding water years were dry, and the water years of 2012- 15 set a record for the driest consecutive four-year period of statewide precipitation.

Patterns of change in high frequency precipitation variability over North America. Roque-Malo S and Kumar P (2017). *Scientific Reports*, 7: 10853.

<http://dx.doi.org/10.1038/s41598-017-10827-8>

Geographic Location: North America

Type of Reference: Research Paper



Abstract: Precipitation variability encompasses attributes associated with the sequencing and duration of events of the full range of magnitudes. However, climate change studies have largely focused on extreme events. Using analyses of long-term weather station data, we show that high frequency events, such as fraction of wet days in a year and average duration of wet and dry periods, are undergoing significant changes across North America. Further, these changes are more prevalent and larger than those associated with extremes. Such trends also exist for events of a range of magnitudes. Existence of localized clusters with opposing trend to that of broader geographic variation illustrates the role of microclimate and other drivers of trends. Such hitherto unknown patterns over the entire North American continent have the potential to significantly inform our characterization of the resilience and vulnerability of a broad range of ecosystems and agricultural and socio-economic systems. They can also set new benchmarks for climate model assessments.

Drought

Drought is characterized by a period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought conditions are historically common in the US Southwest and are anticipated to become more frequent, intense, and longer. An ongoing area of research is determining whether the severity and frequency of droughts in California have already been affected by climate change. Droughts can have significant impacts on the environment, agriculture, public health, the economy, and society as a whole. Shortage of precipitation impinges on crop production and ecosystem function in general (due to soil moisture drought), and affects water supplies. In addition to reductions in precipitation, changes in soil moisture and groundwater are also affected by increases in evaporation and evapotranspiration. The Palmer Drought Severity Index, a measure of the overall dryness of a region, indicates that the 2012-2016 drought in California was the most severe on record.

The extraordinary California drought of 2013/2014: Character, context, and the role of climate change. Swain DL, Tsiang M, Haugen M, Singh D, Charland A, et al. (2014). *Bulletin of American Meteorological Society*, **95**(9): S3-S7.

Geographic Location: California

Type of Reference: Research Paper

Abstract: California's driest 12-month period on record occurred during 2013/14, and although global warming has very likely increased the probability of certain large-scale atmospheric conditions, implications for extremely low precipitation in California remain uncertain.



Global warming and the changes in drought. Trenberth KE, Dai A, van der Schrier G, Jones PD, Barichivich J, Briffa KR, and Sheffield J. (2014). *Nature Climate Change*, 4: 17-22.

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Several recently published studies have produced apparently conflicting results of how drought is changing under climate change. The reason is thought to lie in the formulation of the Palmer Drought Severity Index (PDSI) and the data sets used to determine the evapotranspiration component. Here, we make an assessment of the issues with the PDSI in which several other sources of discrepancy emerge, not least how precipitation has changed and is analysed. As well as an improvement in the precipitation data available, accurate attribution of the causes of drought requires accounting for natural variability, especially El Niño/Southern Oscillation effects, owing to the predilection for wetter land during La Niña events. Increased heating from global warming may not cause droughts but it is expected that when droughts occur they are likely to set in quicker and be more intense.

California's Most Significant Droughts: Comparing Historical and Recent Contributions. California Department of Water Resources (2015).

https://www.water.ca.gov/LegacyFiles/waterconditions/docs/California_Significant_Droughts_2015_small.pdf

Geographic Location: California

Type of Reference: Report

Executive Summary: The water years of 2012-14 stand as California's driest three consecutive years in terms of statewide precipitation, and as of this writing in February 2015 the drought is continuing on. This report was prepared to compare the hydrology and impacts experienced during 2012-2014 with those of California's largest historical droughts, in response to questions from local water agencies and others regarding the drought's relative severity and the changed conditions since our prior major droughts. California's immediately prior drought of statewide scale occurred in 2007-09; it was the first drought for which a statewide proclamation of emergency was issued. The 2012-14 period now marks the second time a statewide proclamation of emergency has been issued for drought.

California's most significant historical statewide droughts were the six-year drought of 1929-34, the two-year drought of 1976-77, and the six-year event of 1987-92. These droughts stand out in the observed record due to their duration or severe hydrology. The 1929-34 event occurred within the climatic context of a decades-plus dry period in the 1920s-30s whose hydrology rivaled that of the most severe dry periods in more than a millennium of reconstructed Central Valley paleoclimate data. The drought's impacts were small by present-day standards, however, since the



state's urban and agricultural development was far less than that of modern times. The 1976-77 drought, although brief in duration, was notable for the severity of its hydrology. The 1987-92 drought was California's first extended dry period since the 1920s-30s, and provides the closest comparison for drought impacts under a present-day level of development.

The 2012-14 event set other records in addition to that of driest three-year period of statewide precipitation. The drought occurred at a time of record warmth in California, with new climate records set in 2014 for statewide average temperatures. Records for minimum annual precipitation were set in many communities in calendar year 2013. Calendar year 2014 saw record-low water allocations for State Water Project and federal Central Valley Project contractors. Reduced surface water availability triggered increased groundwater pumping, with groundwater levels in many parts of the state dropping 50 to 100 feet below their previous historical lows. These record-setting conditions speak to the need for continued improvement of our ability to respond to dry conditions. Knowledge of the impacts historically experienced in our past large droughts and the lessons learned during those events can help us be better prepared.

Storage in California's reservoirs and snowpack in this time of drought.

Dettinger MD and Anderson M (2015). *San Francisco Estuary and Watershed Science*, 13(2). <http://dx.doi.org/10.15447/sfews.2015v13iss2art1>

Geographic Location: California

Type of Reference: Research Paper

Abstract: The San Francisco Bay and Sacramento-San Joaquin Delta (Delta) are the recipients of inflows from a watershed that spans much of California and that has ties to nearly the entire state. Historically, California has buffered its water supplies and flood risks both within-and beyond-the Delta's catchment by developing many reservoirs, large and small, high and low. Most of these reservoirs carry water from wet winter seasons-when water demands are low and flood risks are high-to dry, warm seasons (and years) when demands are high and little precipitation falls. Many reservoirs are also used to catch and delay (or spread in time) flood flows that otherwise might cause damage to communities and floodplains. This essay describes the status of surface-water and snowpack storage conditions in California in spring 2015, providing context for better understanding where the state's water stores stand as we enter summer 2015.



Revisiting the recent California drought as an extreme value. Robeson SM (2015). *Geophysical Research Letters*, **42**(16): 6771-6779.
<http://dx.doi.org/10.1002/2015GL064593>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Spatially weighted averages of Palmer Drought Severity Index (PDSI) over central and southern California show that the 1-year 2014 drought was not as severe as previously reported, but it still is the most severe in the 1895–2014 instrumental record. Using the typical adjustment procedure that matches the mean and standard deviation of tree ring PDSI values to those of instrumental data shows over 10 droughts from 800 to 2006 that were more severe than the 1-year 2014 drought, with the 2014 drought having a return period of 140–180 years. Quantile mapping allows for a closer correspondence between instrumental and tree ring PDSI probability distributions and produces return periods of 700–900 years for the 1-year 2014 drought. Associated cumulative 3 and 4 year droughts, however, are estimated to be much more severe. The 2012–2014 drought is nearly a 10,000 year event, while the 2012–2015 drought has an almost incalculable return period and is completely without precedent.

Causes of the 2011-14 California drought. Seager R, Hoerling M, Schubert S, Wang H, Lyon B, et al. (2015). *Journal of Climate*, **28**(18): 6997-7024.
<http://dx.doi.org/10.1175/JCLI-D-14-00860.1>

Geographic Location: California

Type of Reference: Research Paper

Abstract: The causes of the California drought during November–April winters of 2011/12–2013/14 are analyzed using observations and ensemble simulations with seven atmosphere models forced by observed SSTs. Historically, dry California winters are most commonly associated with a ridge off the west coast but no obvious SST forcing. Wet winters are most commonly associated with a trough off the west coast and an El Niño event. These attributes of dry and wet winters are captured by many of the seven models. According to the models, SST forcing can explain up to a third of California winter precipitation variance. SST forcing was key to sustaining a high pressure ridge over the west coast and suppressing precipitation during the three winters. In 2011/12 this was a response to a La Niña event, whereas in 2012/13 and 2013/14 it appears related to a warm west–cool east tropical Pacific SST pattern. All models contain a mode of variability linking such tropical Pacific SST anomalies to a wave train with a ridge off the North American west coast. This mode explains less variance than ENSO and Pacific decadal variability, and its importance in 2012/13 and 2013/14 was unusual. The models from phase 5 of CMIP (CMIP5) project rising greenhouse gases to cause changes in California all-winter precipitation that are very small compared to recent drought anomalies. However, a long-term warming trend likely contributed to surface moisture deficits during the drought. As such, the precipitation



deficit during the drought was dominated by natural variability, a conclusion framed by discussion of differences between observed and modeled tropical SST trends.

Placing the 2012-2015 California-Nevada drought into a paleoclimatic context: Insights from Walker Lake, California-Nevada, USA. Hatchett BJ, Boyle DP, Putnam AE, and Bassett SD (2015). *Geophysical Research Letters*, **42**(20): 8632-8640. <http://dx.doi.org/10.1002/2015GL065841>

Geographic Location: *California and Nevada*

Type of Reference: *Research Paper*

Abstract: Assessing regional hydrologic responses to past climate changes can offer a guide for how water resources might respond to ongoing and future climate change. Here we employed a coupled water balance and lake evaporation model to examine Walker Lake behaviors during the Medieval Climate Anomaly (MCA), a time of documented hydroclimatic extremes. Together, a ^{14}C -based shoreline elevation chronology, submerged subfossil tree stumps in the West Walker River, and regional paleoproxy evidence indicate a ~50 year pluvial episode that bridged two 140+ year droughts. We developed estimates of MCA climates to examine the transient lake behavior and evaluate watershed responses to climate change. Our findings suggest the importance of decadal climate persistence to elicit large lake-level fluctuations. We also simulated the current 2012–2015 California-Nevada drought and found that the current drought exceeds MCA droughts in mean severity but not duration.

Temperature impacts on the water year 2014 drought in California. Shukla S, Safeeq M, AghaKouchak A, Guan K and Funk C (2015). *Geophysical Research Letters*, **42**(11): 4384-4393. <http://dx.doi.org/10.1002/2015GL063666>

Geographic Location: *California*

Type of Reference: *Research Paper*

Abstract: California is experiencing one of the worst droughts on record. We use a hydrological model and risk assessment framework to understand the influence of temperature on the water year (WY) 2014 drought in California and examine the probability that this drought would have been less severe if temperatures resembled the historical climatology. Our results indicate that temperature played an important role in exacerbating the WY 2014 drought severity. We found that if WY 2014 temperatures resembled the 1916–2012 climatology, there would have been at least an 86% chance that winter snow water equivalent and spring-summer soil moisture and runoff deficits would have been less severe than the observed conditions. We also report that the



temperature forecast skill in California for the important seasons of winter and spring is negligible, beyond a lead time of 1 month, which we postulate might hinder skillful drought prediction in California.

Indications for protracted groundwater depletion after drought over the Central Valley of California. Wang SYS, Lin YH, Gillies RR, and Hakala K (2015). *Journal of Hydrometeorology*, 17(3): 947-955. <http://dx.doi.org/10.1175/JHM-D-15-0105.1>

Geographic Location: California's Central Valley
Type of Reference: Research Paper

Abstract: Ongoing (2014-2015) drought in the state of California has played a major role in the depletion of groundwater. Within California's Central Valley, home to one of the world's most productive agricultural regions, drought and increased groundwater depletion occurs almost hand-in-hand but this relationship appears to have changed over the last decade. Data derived from 497 wells have revealed a continued depletion of groundwater lasting a full year after drought, a phenomenon that was not observed in earlier records before the 21st century. Possible causes include (a) lengthening of drought associated with amplification in the 4-6-year drought frequency since the late 1990s, and (b) intensification of drought and increased pumping that enhances depletion. Altogether, the implication is that groundwater storage in the Central Valley will likely continue to diminish even further in 2016, regardless of the drought status.

Economic Analysis of the 2015 Drought for California Agriculture. Howitt R, MacEwan D, Medellín-Azuara J, Lund J, and Sumner D (2015). UC Davis Center for Watershed Science. Davis, CA. <https://watershed.ucdavis.edu/library/economic-analysis-2015-drought-california-agriculture>

Geographic Location: California
Type of Reference: Report

Introduction: California is in a fourth year of drought – with the last two years being among the driest and warmest individual years on record – raising concerns at all levels, especially in agriculture. Many water districts are intensively using carryover surface and groundwater reserves to ease surface water scarcity. Active ad hoc water markets and other innovations have further softened the economic impacts. Overall, California agriculture remains resilient to this drought thanks to continued growth in value of products, successful local, regional and statewide water management actions, and the state's vast, yet slowly declining groundwater reserves.

We estimate the economic impact of the 2015 drought on agriculture and the effects of continued severe drought in 2016 and 2017. Our research team assessed water



availability for agriculture based on groundwater access estimates, recent surveys of more than 80 irrigation districts, and announcements from federal, state and local projects.

We briefly describe the modeling approach and assumptions and summarize the results. Water availability assessment and groundwater information are detailed in the report appendices.

Annual drought in California: Association with monthly precipitation and climate phases. Shukla S, Steinemann A, Iacobellis SF, and Cayan DR (2015). *Journal of Applied Meteorology and Climatology*, **54**(11). <http://dx.doi.org/10.1175/JAMC-D-15-0167.1>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Annual precipitation in California is more variable than in any other state and is highly influenced by precipitation in winter months. A primary question among stakeholders is whether low precipitation in certain months is a harbinger of annual drought in California. Historical precipitation data from 1895 to 2013 are investigated to identify leading monthly indicators of annual drought in each of the seven climate divisions (CDs) as well as statewide. For this study, drought conditions are defined as monthly/annual (October–September) precipitation below the 20th/30th percentile, and a leading indicator is defined as a monthly drought preceding or during an annual drought that has the strongest association (i.e., joint probability of occurrence) with a statewide annual drought. Monthly precipitation variability and contributions to annual precipitation, along with joint probabilities of drought among the winter months, are first analyzed. Then the probabilities of annual drought and the variability in leading indicators are analyzed according to different climate phases and CDs. This study identified December within a water year as being the leading indicator that is most frequently associated with annual drought statewide (56%) and in most of the CDs (the highest was CD2 at 65%). Associated with its leading-indicator status, December drought was most frequently associated with drought in other winter months (joint probability > 30%). Results from this study can help stakeholders to understand and assess the likelihood of annual drought events given monthly precipitation preceding or early in the water year.

Western water and climate change. Dettinger M, Udall B and Georgakakos A (2015). *Ecological Applications*, **25**(8): 2069-2093. <http://dx.doi.org/10.1890/15-0938.1>

Geographic Location: Western United States

Type of Reference: Review Article



From Abstract: The western United States is a region long defined by water challenges. Climate change adds to those historical challenges, but does not, for the most part, introduce entirely new challenges; rather climate change is likely to stress water supplies and resources already in many cases stretched to, or beyond, natural limits. Projections are for continued and, likely, increased warming trends across the region, with a near certainty of continuing changes in seasonality of snowmelt and streamflows, and a strong potential for attendant increases in evaporative demands. Projections of future precipitation are less conclusive, although likely the northernmost West will see precipitation increases while the southernmost West sees declines. However, most of the region lies in a broad area where some climate models project precipitation increases while others project declines, so that only increases in precipitation uncertainties can be projected with any confidence. Changes in annual and seasonal hydrographs are likely to challenge water managers, users, and attempts to protect or restore environmental flows, even where annual volumes change little. Other impacts from climate change (e.g., floods and water-quality changes) are poorly understood and will likely be location dependent.

In this context, four iconic river basins offer glimpses into specific challenges that climate change may bring to the West. The Colorado River is a system in which overuse and growing demands are projected to be even more challenging than climate-change-induced flow reductions. The Rio Grande offers the best example of how climate-change-induced flow declines might sink a major system into permanent drought. The Klamath is currently projected to face the more benign precipitation future, but fisheries and irrigation management may face dire straits due to warming air temperatures, rising irrigation demands, and warming waters in a basin already hobbled by tensions between endangered fisheries and agricultural demands. Finally, California's Bay-Delta system is a remarkably localized and severe weakness at the heart of the region's trillion-dollar economy. It is threatened by the full range of potential climate-change impacts expected across the West, along with major vulnerabilities to increased flooding and rising sea levels.

A tale of two California droughts: Lessons amidst record warmth and dryness in a region of complex physical and human geography. Swain D (2015). *Geophysical Research Letters*, 42(22). <http://dx.doi.org/10.1002/2015GL066628>

Geographic Location: California
Type of Paper: Review Article

Abstract: The state of California has experienced the worst drought in its historical record during 2012-2015. Adverse effects of this multiyear event have been far from uniformly distributed across the region, ranging from remarkably mild in most of California's densely populated coastal cities to very severe in more rural, agricultural, and wildfire-prone regions. This duality of impacts has created a tale of two very different California droughts-highlighting enhanced susceptibility to climate stresses at the environmental and socioeconomic margins of California. From a geophysical



perspective, the persistence of related atmospheric anomalies has raised a number of questions regarding the drought's origins-including the role of anthropogenic climate change. Recent investigations underscore the importance of understanding the underlying physical causes of extremes in the climate system, and the present California drought represents an excellent case study for such endeavors. Meanwhile, a powerful El Niño event in the Pacific Ocean offers the simultaneous prospect of partial drought relief but also an increased risk of flooding during the 2015-2016 winter-a situation illustrative of the complex hydroclimatic risks California and other regions are likely to face in a warming world.

Substantial increase in concurrent droughts and heatwaves in the United States.

Mazdiyasni O and AghaKouchak A (2015). *Proceedings of the National Academy of Sciences*, **112**(37): 11484-11489. <http://dx.doi.org/10.1073/pnas.1422945112>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: A combination of climate events (e.g., low precipitation and high temperatures) may cause a significant impact on the ecosystem and society, although individual events involved may not be severe extremes themselves. Analyzing historical changes in concurrent climate extremes is critical to preparing for and mitigating the negative effects of climatic change and variability. This study focuses on the changes in concurrences of heatwaves and meteorological droughts from 1960 to 2010. Despite an apparent hiatus in rising temperature and no significant trend in droughts, we show a substantial increase in concurrent droughts and heatwaves across most parts of the United States, and a statistically significant shift in the distribution of concurrent extremes. Although commonly used trend analysis methods do not show any trend in concurrent droughts and heatwaves, a unique statistical approach discussed in this study exhibits a statistically significant change in the distribution of the data.

How has human-induced climate change affected California drought risk?

Cheng L, Hoerling M, AghaKouchak A, Livneh B, Quan X-W, and Eischeid J (2016). *Journal of Climate*, **29**(1): 111-120. <http://dx.doi.org/10.1175/JCLI-D-15-0260.1>

Geographic Location: California

Type of Reference: Research Paper

Abstract: The current California drought has cast a heavy burden on statewide agriculture and water resources, further exacerbated by concurrent extreme high temperatures. Furthermore, industrial-era global radiative forcing brings into question the role of long-term climate change with regard to California drought. How has human-



induced climate change affected California drought risk? Here, observations and model experimentation are applied to characterize this drought employing metrics that synthesize drought duration, cumulative precipitation deficit, and soil moisture depletion. The model simulations show that increases in radiative forcing since the late nineteenth century induce both increased annual precipitation and increased surface temperature over California, consistent with prior model studies and with observed long-term change. As a result, there is no material difference in the frequency of droughts defined using bivariate indicators of precipitation and near-surface (10 cm) soil moisture, because shallow soil moisture responds most sensitively to increased evaporation driven by warming, which compensates the increase in the precipitation. However, when using soil moisture within a deep root zone layer (1 m) as covariate, droughts become less frequent because deep soil moisture responds most sensitively to increased precipitation. The results illustrate the different land surface responses to anthropogenic forcing that are relevant for near-surface moisture exchange and for root zone moisture availability. The latter is especially relevant for agricultural impacts as the deep layer dictates moisture availability for plants, trees, and many crops. The results thus indicate that the net effect of climate change has made agricultural drought less likely and that the current severe impacts of drought on California's agriculture have not been substantially caused by long-term climate changes.

Drought and Equity in California Feinstein L, Phurisamban R, Ford A, Tyler C, and Crawford A (2017). Pacific Institute. Oakland, CA. <http://pacinst.org/publication/drought-equity-california/>

Geographic Location: California

Type of Reference: Report

Abstract: Water is essential for life, yet not everyone in California has access to safe, affordable water. Five years of drought has highlighted these inequities. Recent reviews of the impact of the ongoing drought found that cities and farms, despite feeling the effects of curtailed water supplies, demonstrated great resilience overall. Small water suppliers and natural systems have not fared as well. Some small systems struggled to provide safe water to their customers, thousands of household wells ran dry, and endangered fish reached the brink of extinction. Across California, those on low or fixed incomes have struggled with the rising cost of water.

In this report, we examine three major impacts of the ongoing California drought. The first two, supply shortages and rising costs, affected people's access to safe, affordable water in their homes. We also investigated the impacts of the drought on salmon and, by extension, commercial and tribal fishermen reliant on salmon for income, food, and cultural traditions. We found that low-income households, people of color, and communities already burdened with environmental pollution suffered the most severe impacts. The good news is that there are solutions to these problems, some of which are already being implemented. We conclude with a set of policy recommendations to



improve our ability to cope with drought and minimize its inequitable consequences in the future.

Impacts of the 2014 severe drought on the *Microcystis* bloom in San Francisco Estuary. Lehman PW, Kurobe T, Lesmeister S, Baxa D, Tung A, and Ten SJ (2017). *Harmful Algae*, **63**:94-108.

Geographic Location: San Francisco Estuary (Sacramento-San Joaquin Delta), California

Type of Reference: Research Paper

Abstract: The increased frequency and intensity of drought with climate change may cause an increase in the magnitude and toxicity of freshwater cyanobacteria harmful algal blooms (CHABs), including *Microcystis* blooms, in San Francisco Estuary, California. As the fourth driest year on record in San Francisco Estuary, the 2014 drought provided an opportunity to directly test the impact of severe drought on cyanobacteria blooms in SFE. A field sampling program was conducted between July and December 2014 to sample a suite of physical, chemical, and biological variables at 10 stations in the freshwater and brackish reaches of the estuary. The 2014 *Microcystis* bloom had the highest biomass and toxin concentration, earliest initiation, and the longest duration, since the blooms began in 1999. Median chlorophyll a concentration increased by 9 and 12 times over previous dry and wet years, respectively. Total microcystin concentration also exceeded that in previous dry and wet years by a factor of 11 and 65, respectively. Cell abundance determined by quantitative PCR indicated the bloom contained multiple potentially toxic cyanobacteria species, toxic *Microcystis* and relatively high total cyanobacteria abundance. The bloom was associated with extreme nutrient concentrations, including a 20-year high in soluble reactive phosphorus concentration and low to below detection levels of ammonium. Stable isotope analysis suggested the bloom varied with both inorganic and organic nutrient concentration, and used ammonium as the primary nitrogen source. Water temperature was a primary controlling factor for the bloom and was positively correlated with the increase in both total and toxic *Microcystis* abundance. In addition, the early initiation and persistence of warm water temperature coincided with the increased intensity and duration of the *Microcystis* bloom from the usual 3 to 4 months to 8 months. Long residence time was also a primary factor controlling the magnitude and persistence of the bloom, and was created by a 66% to 85% reduction in both the water inflow and diversion of water for agriculture during the summer. We concluded that severe drought conditions can lead to a significant increase in the abundance of *Microcystis* and other cyanobacteria, as well as their associated toxins.



Greater temperature and precipitation extremes intensify western U.S. droughts, wildfire severity, and Sierra Nevada tree mortality. Crockett JL and Westerling AL (2017). *Journal of Climate*, 31(1): 341-354. <http://dx.doi.org/10.1175/JCLI-D-17-0254.1>

Geographic Location: Western United States

Type of Reference: Research Paper

Abstract: Extensive drought in the western United States (WUS) during the twenty-first century and associated wildfire and tree mortality incidence has highlighted the potential for greater area of severity within widespread droughts. To place recent WUS droughts into a historical context, the authors analyzed gridded daily climate (temperature, precipitation, and climatic water deficit) data to identify and characterize the spatiotemporal evolution of the largest WUS droughts of the last 100 years, with an emphasis on severe cores within drought extents. Cores of droughts during the last 15 years (2000–02 and 2012–14) covered a greater area than in earlier droughts, driven by greater temperature and precipitation extremes. Comparing fire extent and severity before, during, and after drought events using the monitoring trends in burn severity dataset (1984–2014), the authors found fire size and high-severity burn extent were greater during droughts than before or after. Similarly, recent Sierra Nevada forest mortality was greatest in cores immediately after the drought. Climate simulations anticipate greater extremes in temperature and precipitation in a warming world; droughts and related impacts of the last 15 years may presage the effects of these extremes.

Extreme events

An extreme climate event is one which appears only rarely in the historical record, such as a heat wave or a 1-in-100-year flood. Changes in the frequency, intensity, spatial extent, duration and timing of extreme events can occur in a changing climate. Global evidence since 1950 indicates a change in some extremes (such as a decrease in the number of cold days and nights and an overall increase in the number of warm days and nights). Extreme events usually result from a combination of factors. There is much interest in the science community in determining to what extent, if any, anthropogenic climate change can influence extreme events.

Climate change, climate justice and the application of probabilistic event attribution to summer heat extremes in the California Central Valley. Mera R, Massey N, Rupp DE, Mote P, Allen M and Frumhoff PC (2015). *Climatic Change*, 133(3): 427-438. <http://dx.doi.org/10.1007/s10584-015-1474-3>

Geographic Location: California's Central Valley

Type of Reference: Research Paper



Abstract: Probabilistic event attribution (PEA) is an important tool for assessing the contribution of climate change to extreme weather events. Here, PEA is applied to explore the climate attribution of recent extreme heat events in California's Central Valley. Heat waves have become progressively more severe due to increasing relative humidity and nighttime temperatures, which increases the health risks of exposed communities, especially Latino farmworkers and other socioeconomically disadvantaged communities. Using a superensemble of simulations with the Hadley Centre Regional Model (HadRM3P), we find that (1) simulations of the hottest summer days during the 2000s were twice as likely to occur using observed levels of greenhouse gases than in a counterfactual world without major human activities, suggesting a strong relationship between heat extremes and the increase in human emissions of greenhouse gases, (2) detrimental impacts of heat on public health-relevant variables, such as the number of days above 40 °Celsius, can be quantified and attributed to human activities using PEA, and (3) PEA can serve as a tool for addressing climate justice concerns of populations within developed nations who are disproportionately exposed to climate risks.

Attribution of climate extreme events. Trenberth KE, Fasullo JT, and Shepherd TG (2015). *Nature Climate Change*, 5: 725-730. <http://dx.doi.org/10.1038/nclimate2657>

Geographic Location: Global

Type of Reference: Review Article

Abstract: There is a tremendous desire to attribute causes to weather and climate events that is often challenging from a physical standpoint. Headlines attributing an event solely to either human-induced climate change or natural variability can be misleading when both are invariably in play. The conventional attribution framework struggles with dynamically driven extremes because of the small signal-to-noise ratios and often uncertain nature of the forced changes. Here, we suggest that a different framing is desirable, which asks why such extremes unfold the way they do. Specifically, we suggest that it is more useful to regard the extreme circulation regime or weather event as being largely unaffected by climate change, and question whether known changes in the climate system's thermodynamic state affected the impact of the particular event. Some examples briefly illustrated include 'snowmageddon' in February 2010, superstorm Sandy in October 2012 and supertyphoon Haiyan in November 2013, and, in more detail, the Boulder floods of September 2013, all of which were influenced by high sea surface temperatures that had a discernible human component.



Attribution of extreme weather and climate-related events. Stott PA, Christidis N, Otto FL, Sun Y, Vanderlinden JP, et al. (2016). *WIREs Climate Change*, 7: 23-41. <http://dx.doi.org/10.1002/wcc.380>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Extreme weather and climate-related events occur in a particular place, by definition, infrequently. It is therefore challenging to detect systematic changes in their occurrence given the relative shortness of observational records. However, there is a clear interest from outside the climate science community in the extent to which recent damaging extreme events can be linked to human-induced climate change or natural climate variability. Event attribution studies seek to determine to what extent anthropogenic climate change has altered the probability or magnitude of particular events. They have shown clear evidence for human influence having increased the probability of many extremely warm seasonal temperatures and reduced the probability of extremely cold seasonal temperatures in many parts of the world. The evidence for human influence on the probability of extreme precipitation events, droughts, and storms is more mixed. Although the science of event attribution has developed rapidly in recent years, geographical coverage of events remains patchy and based on the interests and capabilities of individual research groups. The development of operational event attribution would allow a more timely and methodical production of attribution assessments than currently obtained on an *ad hoc* basis. For event attribution assessments to be most useful, remaining scientific uncertainties need to be robustly assessed and the results clearly communicated. This requires the continuing development of methodologies to assess the reliability of event attribution results and further work to understand the potential utility of event attribution for stakeholder groups and decision makers.

Fog, lightning and other climate phenomena

Changing temperatures can influence other climate phenomena, including fog, lightning and winds. Warming temperatures can have a strong influence on some of the processes affecting fog formation. On a local scale, differences in the rate of heating and cooling of land versus bodies of water greatly affect wind formation. Air temperatures have also been shown to influence lightning activity.

Projected increase in lightning. Roms DM, Seeley JT, Vollaro D, and Molinari J (2014). *Science*, 346(6211): 851-854. <http://dx.doi.org/10.1126/science.1259100>

Geographic Location: United States

Type of Reference: Research Paper



Abstract: Lightning plays an important role in atmospheric chemistry and in the initiation of wildfires, but the impact of global warming on lightning rates is poorly constrained. Here we propose that the lightning flash rate is proportional to the convective available potential energy (CAPE) times the precipitation rate. Using observations, the product of CAPE and precipitation explains 77% of the variance in the time series of total cloud-to-ground lightning flashes over the contiguous United States (CONUS). Storms convert CAPE times precipitated water mass to discharged lightning energy with an efficiency of 1%. When this proxy is applied to 11 climate models, CONUS lightning strikes are predicted to increase $12 \pm 5\%$ per degree Celsius of global warming and about 50% over this century.

Coastal fog, climate change, and the environment. Torregrosa A, O'Brien TA, and Faloona IC (2014). *Eos, Transactions American Geophysical Union*, **95**(50): 473-474. <http://dx.doi.org/10.1002/2014EO500001>

Geographic Location: Global, with emphasis on California coast
Type of Reference: Article

Excerpt from introductory text: To climate scientists, fog's physical opacity symbolizes how much remains to be discovered about it. They know the importance of the summertime shade and moisture provided by the onshore transport of fog arriving as a wall of marine cloud. However, empirical data or physical models capable of characterizing fog as a climatological phenomenon are surprisingly sparse. One pressing question involves how global climate change will influence fog and how fog may be affected by rising surface temperatures and secondary effects such as coastal wind strength, inland marine layer intrusion, and increased evaporation. Changes in fog frequency have implications for a wide range of sectors, including coastal ecology, agriculture, urban energy and water consumption, and public health. To help coastal communities, many climate scientists are taking a close look at fog with the aim of developing models of future fog patterns.

Cool PDO phase leads to recent rebound in coastal southern California fog. Witiw MR and LaDochy S (2015). *Journal of the Geographical Society of Berlin*, **146**(4), 232-244.

Geographic Location: Southern California
Type of Reference: Research Paper

Abstract: The relationship between coastal fog in southern California and the Pacific Decadal Oscillation (PDO) is investigated during the last decade. Fog occurrence was examined at two locations in southern California: San Diego and Los Angeles international airports. Both locations are located near the Pacific coast with strong marine influences. The period looked at was 2001 through 2012. The cool season



(October-March) and warm season (April-September) were examined separately because of the different types of fog that prevail in each season. Previous studies have shown a relation between fog and the Pacific Decadal Oscillation (PDO). However, a switch in polarity in the PDO in the mid-1970s (from a cool to a warm phase) coupled with a sharp decrease in particulate concentrations calls into question the strong relationship shown. Further studies suggest that the decrease in dense fog seen from the 1960s through the 1990s was largely due to increasing urban heat island effects coupled with a decrease in atmospheric particulate matter. Since 1998, the PDO again changed polarity and fog frequencies began to rise. However, urban heat island and particulate effects were relatively constant making it easier to isolate any effects of the PDO on fog occurrence. Previous studies examined the occurrence of dense fog (visibility less than 400 meters), but because of the decrease in fog in this category, 800 meters was chosen this time. That also corresponds to the 0.5 mile visibility which triggers special reports at the California airports when visibility moves through this threshold. Although there was no strong relationship between fog and PDO in the most recent period, Pacific Ocean oscillations were found to show significant relationships with fog frequencies historically. Upwelling indices show a significant relationship with fog frequencies when examined by the phase of the PDO. Even stronger relationships are found when selecting La Niña and El Niño events.

Interannual variability of sea fog frequency in the Northwestern Pacific in July. Zhang S, Chen Y, Long J, and Han G (2015). *Atmospheric Research*, **151**: 189-199. <http://dx.doi.org/10.1016/j.atmosres.2014.04.004>

Geographic Location: Northwestern Pacific Ocean

Type of Reference: Research Paper

Abstract: The interannual variability in the sea fog frequency (SFF) in July in the midlatitude Northwestern Pacific (40°N–50°N, 140°E–170°W) from 1979 to 2009 is investigated with observations and reanalysis datasets. Composite analysis shows that in high-SSF years the center of the Northwestern Pacific subtropical high (SH) shifts eastward and a strengthened ridge exists in the midlatitude Northwestern Pacific. Under such conditions, large amount of moisture from the subtropics are transported northwardly by the southerlies over the west flank of the SH. The ridge is helpful for stable stratification and conducive to fog formation. In contrast, in low-SFF years the center of the SH expands westward and drifts further south; thus moisture can hardly reach the midlatitudes. Meanwhile an anomalous trough in the midlatitudes and the associated anomalous northerlies both weaken the southerlies and reduce the stability, unfavorable for fog occurrence. The case studies confirmed that the air parcels moving from the subtropical zone to the midlatitudes controlled by the SH, kept the higher temperature and humidity when flowing across the Kuroshio Extension, and then cooled down over the cold oceanic surface in fog case. The SFF in the Northwestern Pacific would decline under the conditions of global warming.



Fog drip maintains dry season ecological function in a California coastal pine forest. Fischer DT, Still CJ, Ebert CM, Baguskas SA, and Williams AP (2016). *Ecosphere*, 7(6): e01364. <http://dx.doi.org/10.1002/ecs2.1364>

Geographic Location: Santa Cruz Island, California

Type of Reference: Research Paper

Abstract: Fog drip is recognized as an important source of water for many ecosystems that often harbor a disproportionate fraction of endemic species. Characterizing and quantifying the ecological importance of fog drip in these ecosystems requires a range of approaches. We report on a multi-faceted study of Bishop pine (*Pinus muricata* D. Don) along a coastal-inland transect on an island off Southern California. Hourly sampling included micrometeorology, sap flux, and soil moisture. Monthly measurements included changes in tree girth, plant water stress, and isotopic values of fogwater, rainwater, and xylem water. These data show that summertime fog drip clearly affected soil moisture and maintained aspects of tree function, including leaf water relations, sap flux dynamics, and growth rates. Although water from fog drip to the soil surface was occasionally taken up by pine trees, as quantified with isotopic measurements and a Bayesian mixing model, this utilization of fog drip was highly variable in space and time. The proportion of fogwater inferred to have been used is also much less than has been demonstrated in more mesic coastal forest ecosystems using isotopic methods. These results thus suggest high ecosystem sensitivity to even moderate amounts of fog drip, a finding with important implications as climate change differentially affects fog and rain patterns.

What causes observed fog trends: Air quality or climate change? Klemm O and Lin NH (2016). *Aerosol and Air Quality Research*, 16: 1131–1142. <http://dx.doi.org/10.4209/aaqr.2015.05.0353>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Fog is a situation when the visual range, which is the horizontal visibility, is reduced to less than 1000 meters near the Earth's surface by the presence of cloud droplets. Fog trend analyses are reported in the literature for hundreds of stations worldwide, the majority of which showing a considerable reduction of fog. Although fog is often associated with conditions at which cloud condensation nuclei had been activated at rH (relative humidity) $> 100\%$ and rapid growth had led to the formation of fog droplets, this study focusses on urban air masses and conditions when rH is just below 100 percent. Mie scattering analysis shows that fog can form under such conditions and the reduction of the visual range is mainly caused by submicron aerosol particles which grow to diameters around $1\ \mu m$ through deliquescence. The liquid water content itself is poorly correlated with the visual range. Assuming equilibrium conditions, both an increase of the air temperature and a reduction of the aerosol particle concentration lead to reductions of fog. In our example case, the increment for a



temperature increase by 0.1°Celsius had about the same effect as the reduction of aerosol concentrations by 10 percent. Care must be taken in projecting this result to actual conditions because the system is non-linear. However, physical evidence is presented which confirms that both climate change and an improvement of air quality are mechanisms that can contribute to the reduction of fog.

The northward march of summer low cloudiness along the California coast.

Clemesha RES, Gershunov A, Iacobellis SF, Williams AP, and Cayan DR (2016).

Geophysical Research Letters, **43**(3): 1287-1295.

<http://dx.doi.org/10.1002/2015GL067081>

Geographic Location: California coast

Type of Reference: Research Paper

Abstract: A new satellite-derived low cloud retrieval reveals rich spatial texture and coherent space-time propagation in summertime California coastal low cloudiness (CLC). Throughout the region, CLC is greatest during May-September but has considerable monthly variability within this summer season. On average, June is cloudiest along the coast of southern California and northern Baja, Mexico, while July is cloudiest along northern California's coast. Over the course of the summer, the core of peak CLC migrates northward along coastal California, reaching its northernmost extent in late July/early August, then recedes while weakening. The timing and movement of the CLC climatological structure is related to the summer evolution of lower tropospheric stability and both its component parts, sea surface temperature and potential temperature at 700 hectoPascal. The roughly coincident seasonal timing of peak CLC with peak summertime temperatures translates into the strongest heat-modulating capacity of CLC along California's north coast.

A projected decrease in lightning under climate change. Finney D, Doherty R, Wild O, Stevenson DS, MacKenzie IA, Blyth AM (2018). *Nature Climate Change* **8**: 210-213.

Geographic Location: Global

Type of Reference: Research Paper

Lightning strongly influences atmospheric chemistry, and impacts the frequency of natural wildfires. Most previous studies project an increase in global lightning with climate change over the coming century, but these typically use parameterizations of lightning that neglect cloud ice fluxes, a component generally considered to be fundamental to thunderstorm charging. As such, the response of lightning to climate change is uncertain. Here, we compare lightning projections for 2100 using two parameterizations: the widely used cloud-top height (CTH) approach, and a new upward cloud ice flux (IFLUX) approach that overcomes previous limitations. In contrast to the previously reported global increase in lightning based on CTH, we find a 15% decrease



in total lightning flash rate with IFLUX in 2100 under a strong global warming scenario. Differences are largest in the tropics, where most lightning occurs, with implications for the estimation of future changes in tropospheric ozone and methane, as well as differences in their radiative forcings. These results suggest that lightning schemes more closely related to cloud ice and microphysical processes are needed to robustly estimate future changes in lightning and atmospheric composition.



Impacts of Climate Change on Physical Systems

Physical systems include the ocean, coastal and freshwater systems and the cryosphere (snow, ice and frozen ground). These systems are intricately linked to climate and to each other. Observed changes in these systems may reflect a response to long-term climate change or to patterns of natural climate variability, such as the El Niño/La Niña Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation or all of them. Examples of impacts include erosion, sea level rise, salt water intrusion, and changes in snowmelt runoff. Many of these observed changes are the direct result of rising temperatures. This chapter lists publications on: changes in ocean temperature and circulation; upwelling; sea level rise; and snowmelt and other freshwater impacts.

Changes in ocean temperature and circulation

The ocean plays an important role in climate variability and change. Ocean circulation transfers heat from the oceans to the atmosphere, and distributes heat between the equatorial and polar regions. Ocean processes vary over a broad range of time scales. The main modes of climate variability most relevant to California are the ENSO and the PDO. ENSO is an ocean-atmosphere system in the tropical Pacific marked by El Niño events, which occur about every three to seven years and bring warm rainy weather, alternating with periods of below-average temperatures (La Niña). The more northerly PDO, an atmospheric circulation pattern, is often described as a long-lived El Niño-like pattern, extending from 20 to 40 years. Its extreme phases are classified as being either warm or cool, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean.

Global ocean temperatures have been increasing. The oceans have absorbed an estimated 84 percent of the heat added to the atmosphere between 1955 and 2008, increasing the average temperature of the upper 700 meters of water by 0.2° Celsius (0.36°F). Observed temperature increases around the globe have been uneven, as they are governed by atmospheric factors (such as wind speed and air temperature) and oceanic processes (such as currents and vertical mixing).¹

¹ U.S. Global Change Research Program (2012). *Oceans and Marine Resources in a Changing Climate: Technical Input to the 2013 National Climate Assessment.*



Probable causes of the abnormal ridge accompanying the 2013-2014 California drought: ENSO precursor and anthropogenic warming footprint. Wang S-Y, Hipps L, Gilles RR and Yoon JH (2014). *Geophysical Research Letters*, **41**(9): 3220-3226. <http://dx.doi.org/10.1002/2014GL059748>

Geographic Location: North Pacific Ocean

Type of Reference: Research Paper

Abstract: The 2013–2014 California drought was initiated by an anomalous high-amplitude ridge system. The anomalous ridge was investigated using reanalysis data and the Community Earth System Model (CESM). It was found that the ridge emerged from continual sources of Rossby wave energy in the western North Pacific starting in late summer and subsequently intensified into winter. The ridge generated a surge of wave energy downwind and deepened further the trough over the northeast U.S., forming a dipole. The dipole and associated circulation pattern is not linked directly with either El Niño–Southern Oscillation (ENSO) or Pacific Decadal Oscillation; instead, it is correlated with a type of ENSO precursor. The connection between the dipole and ENSO precursor has become stronger since the 1970s, and this is attributed to increased greenhouse gas loading as simulated by the CESM. Therefore, there is a traceable anthropogenic warming footprint in the enormous intensity of the anomalous ridge during winter 2013–2014 and the associated drought.

Causes and impacts of the 2014 warm anomaly in the NE Pacific. Bond NA, Cronin MF, Freeland H, and Mantua N (2015). *Geophysical Research Letters*, **42**(9): 3414-3420. <http://dx.doi.org/10.1002/2015GL063306>

Geographic Location: Northeast Pacific Ocean

Type of Reference: Research Paper

Abstract: Strongly positive temperature anomalies developed in the northeast Pacific Ocean during the boreal winter of 2013–2014. Based on a mixed layer temperature budget, these anomalies were caused by lower than normal rates of the loss of heat from the ocean to the atmosphere and of relatively weak cold advection in the upper ocean. Both of these mechanisms can be attributed to an unusually strong and persistent weather pattern featuring much higher than normal sea level pressure over the waters of interest. This anomaly was the greatest observed in this region since at least the 1980s. The region of warm sea surface temperature anomalies subsequently expanded and reached coastal waters in spring and summer 2014. Impacts on fisheries and regional weather are discussed. It is found that sea surface temperature anomalies in this region affect air temperatures downwind in Washington state.



The Blob' invades Pacific, flummoxing climate experts. Kintisch E (2015). *Science*, 348(6230): 17-18. <http://dx.doi.org/10.1126/science.348.6230.17>

Geographic Location: Pacific Ocean

Type of Reference: Review Article

Abstract: Researchers are studying the drivers and impacts of a massive "blob" of warmer-than-usual water off the Pacific coast that has persisted since fall 2013. The water, 2000 kilometer wide and 100 meter deep, has affected ecosystems, changed weather inland, and altered ocean currents from Alaska to Mexico. The main culprits appear to be a massive low-pressure system that appeared in late 2013, though since then The Blob appears to be part of a warm phase of the Pacific Decadal Oscillation, a set of phenomena that provided prolonged heating in the eastern Pacific every 4 to 20 years. Researchers have already blamed die-offs of migratory birds and sea lions on The Blob; concerns are now that salmon harvests this summer will be depressed as a result of the warm water.

State of the California Current 2014–15: Impacts of the warm-water “Blob”.

Leising AW, Schroeder ID, Bograd SJ, Abell J, Durazo, R, and Warybok P (2015). *CalCOFI Reports*, 56: 31-68. <http://calcofi.org/publications/calcofireports/v56/Vol56-SOTCC.web.31-69.pdf>

Geographic Location: California Current, Pacific Ocean

Type of Reference: Report

Abstract: In 2014, the California Current (~28°–48°N) saw average, or below average, coastal upwelling and relatively low productivity in most locations, except from 38°–43°N during June and July. Chlorophyll-a levels were low throughout spring and summer at most locations, except in a small region around 39°N. Catches of juvenile rockfish (an indicator of upwelling-related fish species) remained high throughout the area surveyed (32°–43°N). In the fall of 2014, as upwelling ceased, many locations saw an unprecedented increase in sea surface temperatures (anomalies as large as 4° Celsius), particularly at 45°N due to the coastal intrusion of an extremely anomalous pool of warm water. This warm surface anomaly had been building offshore in the Gulf of Alaska since the fall of 2013, and has been referred to as the “blob.” Values of the Pacific Decadal Oscillation index (PDO) continued to climb during 2014, indicative of the increase in warm coastal surface waters, whereas the North Pacific Gyre Oscillation index (NPGO) saw a slight rebound to more neutral values (indicative of average productivity levels) during 2014. During spring 2015, the upwelling index was slightly higher than average for locations in the central and northern region, but remained below average at latitudes south of 35°N. Chlorophyll a levels were slightly higher than average in ~0.5° latitude patches north of 35°N, whereas productivity and phytoplankton biomass were low south of Pt. Conception. Catches of rockfish remained high along most of the coast, however, market squid remained high only within the central coast (36°–38°N), and euphausiid abundance decreased everywhere, as compared to the



previous year. Sardine and anchovy were nearly absent from the southern portion of the California Current system (CCS), whereas their larvae were found off the coast of Oregon and Washington during winter for the first time in many years. Waters warmed dramatically in the southern California region due to a change in wind patterns similar to that giving rise to the blob in the broader northeast Pacific. For most of the coast, there were intrusions of species never found before or found at much higher abundances than usual, including fish, crustaceans, tunicates and other gelatinous zooplankton, along with other species often indicative of an El Niño. Thus species richness was high in many areas given the close juxtaposition of coastal upwelling-related species with the offshore warm-water intrusive or El Niño-typical taxa. Thus the California Current by 2015 appears to have transitioned to a very different state than previous observations.

State of the California Current 2015-16: Comparisons with the 1997–98 El Niño.

McClatchie S (2016). *CalCOFI Reports*, **57**:5-108.

http://cetus.ucsd.edu/Publications/Publications/Vol57-SOTCC_pages.5-61.pdf

Geographic Location: California Current, Pacific Ocean

Type of Reference: Report

From abstract: Warm conditions in the North Pacific in 2014–15 were a result of the continuation of the North Pacific marine heat wave, a large area of exceptionally high SST anomalies that originated in the Gulf of Alaska in late 2013. The North Pacific heat wave interacted with an El Niño developing in the equatorial Pacific in 2015. Weekly periods of exceptionally high temperature anomalies ($>2^{\circ}\text{C}$) occurred until the start of the El Niño (winter of 2015), when SSTs were still high but not as high as those due to the marine heat wave. During the 2015–16 El Niño, the depth of the 26.0 kg m^{-3} isopycnal ($\sigma_{26.0}$) was considerably shallower than during the 1982–83 and 1997–98 events. The area affected by the marine heat wave and the 2015–16 El Niño in the mixed layer was comparable to the 1997–98 El Niño, but lasted longer. Water column stratification in the upper 100 m during 2015–16 was as strong as the most extreme values during the 1997–98 El Niño. This stratification was primarily driven by the warming of the upper 100 m. Despite notable perturbations, the effects of the 2015–16 El Niño on hydrographic properties in the CalCOFI domain were not as strong as those observed during the 1997–98 El Niño.

State of the California Current 2016-17: Still anything but “normal” in the north.

Schroeder ID, Bograd SJ, Hazen EL, Jacox MG, Leising A, et al. (2016). *CalCOFI Reports*, **58**(58).

[http://calcofi.org/publications/calcofireports/v58/Vol58-State of the Current pages 1-55.pdf](http://calcofi.org/publications/calcofireports/v58/Vol58-State%20of%20the%20Current%20pages%201-55.pdf)

Geographic Location: California Current, Pacific Ocean

Type of Reference: Report



From abstract: This report examines the ecosystem state of the California Current System (CCS) from spring 2016–spring 2017. Basin-scale indices suggest conditions that would support average to below average coast-wide production across the CCS during this time period. Regional surveys in 2016 sampled anomalously warm surface and subsurface waters across the CCS. Chlorophyll concentrations were low across the CCS in 2016 and, concomitant with that, copepod communities had an anomalously high abundance of subtropical species. Early in 2017 conditions between northern, central, and southern CCS were dissimilar. Specifically, surface conditions north of Cape Mendocino remained anomalously warm, chlorophyll was very low, and subtropical copepods were anomalously abundant. Southern and central CCS surveys indicated that environmental conditions and chlorophyll were within normal ranges for the longer time series, supporting an argument that biophysical conditions/ ecosystem states in the southern and central CCS were close to normal.

Multi-year persistence of the 2014/15 North Pacific marine heatwave. Di Lorenzo E and Mantua NJ (2016). *Nature Climate Change*, 6(11).
<http://dx.doi.org/10.1038/nclimate3082>

Geographic Location: North Pacific Ocean
Type of Reference: Research Paper

Abstract: Between the winters of 2013/14 and 2014/15 during the strong North American drought, the northeast Pacific experienced the largest marine heatwave ever recorded. Here we combine observations with an ensemble of climate model simulations to show that teleconnections between the North Pacific and the weak 2014/2015 El Niño linked the atmospheric forcing patterns of this event. These teleconnection dynamics from the extratropics to the tropics during winter 2013/14, and then back to the extratropics during winter 2014/15, are a key source of multi-year persistence of the North Pacific atmosphere. The corresponding ocean anomalies map onto known patterns of North Pacific decadal variability, specifically the North Pacific Gyre Oscillation (NPGO) in 2014 and the Pacific Decadal Oscillation (PDO) in 2015. A large ensemble of climate model simulations predicts that the winter variance of the NPGO- and PDO-like patterns increases under greenhouse forcing, consistent with other studies suggesting an increase in the atmospheric extremes that lead to drought over North America.

Trends in atmospheric patterns conducive to seasonal precipitation and temperature extremes in California. Swain DL, Horton DE, Singh D, and Diffenbaugh NS (2016). *Science Advances*, 2(4): e1501344.
<http://dx.doi.org/10.1126/sciadv.1501344>

Geographic Location: California
Type of Reference: Research Paper



Abstract: Recent evidence suggests that changes in atmospheric circulation have altered the probability of extreme climate events in the Northern Hemisphere. We investigate northeastern Pacific atmospheric circulation patterns that have historically (1949–2015) been associated with cool-season (October–May) precipitation and temperature extremes in California. We identify changes in occurrence of atmospheric circulation patterns by measuring the similarity of the cool-season atmospheric configuration that occurred in each year of the 1949–2015 period with the configuration that occurred during each of the five driest, wettest, warmest, and coolest years. Our analysis detects statistically significant changes in the occurrence of atmospheric patterns associated with seasonal precipitation and temperature extremes. We also find a robust increase in the magnitude and sub-seasonal persistence of the cool-season West Coast ridge, resulting in an amplification of the background state. Changes in both seasonal mean and extreme event configurations appear to be caused by a combination of spatially nonuniform thermal expansion of the atmosphere and reinforcing trends in the pattern of sea level pressure. In particular, both thermal expansion and sea level pressure trends contribute to a notable increase in anomalous northeastern Pacific ridging patterns similar to that observed during the 2012–2015 California drought. Collectively, our empirical findings suggest that the frequency of atmospheric conditions like those during California’s most severely dry and hot years has increased in recent decades, but not necessarily at the expense of patterns associated with extremely wet years.

Satellite sea surface temperatures along the West Coast of the United States during the 2014–2016 northeast Pacific marine heat wave. Gentemann CL, Fewings MR, and García-Reyes M (2017). *Geophysical Research Letters*, **44**(1): 312–319. <http://dx.doi.org/10.1002/2016GL071039>

Geographic Location: West coast/Pacific Ocean
Type of Reference: Research Paper

Abstract: From January 2014 to August 2016, sea surface temperatures (SSTs) along the Washington, Oregon, and California coasts were significantly warmer than usual, reaching a maximum SST anomaly of 6.2°Celsius off Southern California. This marine heat wave occurred alongside the Gulf of Alaska marine heat wave and resulted in major disturbances in the California Current ecosystem and massive economic impacts. Here we use satellite and blended reanalysis products to report the magnitude, extent, duration, and evolution of SSTs and wind stress anomalies along the West Coast of the continental United States during this event. Nearshore SST anomalies along the entire coast were persistent during the marine heat wave, and only abated seasonally, during spring upwelling-favorable wind stress. The coastal marine heat wave weakened in July 2016 and disappeared by September 2016.



California multivariate ocean climate indicator (MOCI) and marine ecosystem dynamics. García-Reyes M and Sydeman WJ (2017). *Ecological Indicators*, 72: 521-529. <http://dx.doi.org/10.1016/j.ecolind.2016.08.045>

Geographic Location: California Coast

Type of Reference: Research Paper

Abstract: Marine ecosystems are complex adaptive systems with physical and biological processes operating on multiple spatial and temporal scales. Here, we present an operational regional indicator for California's continental shelf system and investigate its skill in predicting a variety of biological responses across trophic levels. This updated Multivariate Ocean Climate Indicator (MOCI) version 2 includes data that are readily available from the Internet so the indicator can be automatically updated and shared regularly. MOCIV.2 is a simplified version of MOCIV.1, but it captures ocean-climate variability similarly. MOCIV.2 illustrates all major ENSO events that occurred over the past 25 years as well as the phasing and magnitude of the most recent North Pacific marine heat wave, dubbed 'The Blob'. It also shows differences in the magnitude and timing of ocean-climate variability in different regions off California. MOCIV.2 has skill in nowcasting marine ecosystem dynamics, from zooplankton to top predators, and therefore may be useful in establishing bio-physical relationships important to ecosystem-based fisheries and wildlife management in California.

Longer and more frequent marine heatwaves over the past century. Oliver ECJ, Donat MG, Burrows MT, Moore PJ, Smale DA, et al. (2018). *Nature Communications*, 9(1324). <http://dx.doi.org/10.1038/s41467-018-03732-9>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Heatwaves are important climatic extremes in atmospheric and oceanic systems that can have devastating and long-term impacts on ecosystems, with subsequent socioeconomic consequences. Recent prominent marine heatwaves have attracted considerable scientific and public interest. Despite this, a comprehensive assessment of how these ocean temperature extremes have been changing globally is missing. Using a range of ocean temperature data including global records of daily satellite observations, daily in situ measurements and gridded monthly in situ-based data sets, we identify significant increases in marine heatwaves over the past century. We find that from 1925 to 2016, global average marine heatwave frequency and duration increased by 34% and 17%, respectively, resulting in a 54% increase in annual marine heatwave days globally. Importantly, these trends can largely be explained by increases in mean ocean temperatures, suggesting that we can expect further increases in marine heatwave days under continued global warming.



Changes in dissolved oxygen levels

Ocean chemistry is influenced by many physical and biological processes, including currents, sediments, atmospheric constituents and ecological systems. Optimal levels of dissolved oxygen are important for marine habitats. Warmer waters hold less oxygen. As the ocean warms, the amount of dissolved oxygen declines. Declining oxygen concentrations can lead to significant ecological changes in marine ecosystems, including wide-ranging impacts on species diversity and abundance, and marine food webs. Changing ocean chemistry, in concert with changes in temperature, may lead to even greater and more widespread impacts on coastal marine ecosystems.

Changes in source waters to the Southern California Bight. Bograd SJ, Buil MP, Di Lorenzo E, Castro CG, Schroeder ID, et al. (2015). *Deep-Sea Research Part II: Topical Studies in Oceanography*, **112**: 42-52.
<http://dx.doi.org/10.1016/j.dsr2.2014.04.009>

Geographic Location: Southern California Bight, Pacific Ocean
Type of Reference: Research Paper

Abstract: Historical hydrographic data (1984–2012) from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program and global reanalysis products were used to quantify recent water mass variability off the coast of Southern California. Dissolved oxygen concentrations continued to decline within the lower pycnocline, concurrent with strong increases in nitrate and phosphate that have spatial patterns matching those of dissolved oxygen. Silicic acid also shows an increasing trend in the offshore portion of the region, but has strong and opposing trends in the upper (increasing) and lower-pycnocline (decreasing) within the Southern California Bight. The varying rates of change in the inorganic nutrients yield a more complex pattern of variability in the nutrient ratios, resulting in large decreases in the N:P and Si:N ratios within the Southern California Bight at depths that provide source waters for upwelling. Basin-scale reanalysis products are consistent with low-frequency water mass changes observed off Southern California and suggest that advection of modified source waters is the cause of the variability. The biogeochemical changes described here may have important impacts on the regional ecosystem, including a reduction of viable pelagic habitat and community reorganization.

Declining oxygen in the global ocean and coastal waters. Breitburg D, Levin LA, Oschlies A, Grégoire M, Chavez FP, et al (2018). *Science*, **359**(6371): eaam7240.
<http://dx.doi.org/10.1126/science.aam7240>

Geographic Location: Global
Type of Reference: Review Article



Abstract: As plastic waste pollutes the oceans and fish stocks decline, unseen below the surface another problem grows: deoxygenation. Breitburg *et al.* review the evidence for the downward trajectory of oxygen levels in increasing areas of the open ocean and coastal waters. Rising nutrient loads coupled with climate change—each resulting from human activities—are changing ocean biogeochemistry and increasing oxygen consumption. This results in destabilization of sediments and fundamental shifts in the availability of key nutrients. In the short term, some compensatory effects may result in improvements in local fisheries, such as in cases where stocks are squeezed between the surface and elevated oxygen minimum zones. In the longer term, these conditions are unsustainable and may result in ecosystem collapses, which ultimately will cause societal and economic harm.

Upwelling

The California Current is a seasonal southward-flowing ocean current that transports cool, low salinity- and nutrient-rich water from sub-Arctic regions to the California coast. A regional wind-driven process known as “upwelling” carries the deep, cooler waters transported by the current closer to the surface where photosynthesis stimulates the growth and reproduction of phytoplankton. Climate change impacts on winds may be changing the upwelling patterns and impacting marine ecosystems.

Under pressure: Climate change, upwelling, and eastern boundary upwelling ecosystems. Garcia-Reyes M, Sydeman WJ, Schoeman DS, Rykaczewski RR, Black BA, et al. (2015). *Frontiers in Marine Science*, 2: 109.
<http://dx.doi.org/10.3389/fmars.2015.00109>

Geographic Location: California Current System, Canary Current System, Humboldt Current System, and Benguela Current System
Type of Reference: Review Article

Abstract: The IPCC AR5 provided an overview of the likely effects of climate change on Eastern Boundary Upwelling Systems (EBUS), stimulating increased interest in research examining the issue. We use these recent studies to develop a new synthesis describing climate change impacts on EBUS. We find that model and observational data suggest coastal upwelling-favorable winds in poleward portions of EBUS have intensified and will continue to do so in the future. Although evidence is weak in data that are presently available, future projections show that this pattern might be driven by changes in the positioning of the oceanic high-pressure systems rather than by deepening of the continental low-pressure systems, as previously proposed. There is low confidence regarding the future effects of climate change on coastal temperatures and biogeochemistry due to uncertainty in the countervailing responses to increasing upwelling and coastal warming, the latter of which could increase thermal stratification and render upwelling less effective in lifting nutrient-rich deep waters into the photic zone. Although predictions of ecosystem responses are uncertain, EBUS experience



considerable natural variability and may be inherently resilient. However, multi-trophic level, end-to-end (i.e., "winds to whales") studies are needed to resolve the resilience of EBUS to climate change, especially their response to long-term trends or extremes that exceed pre-industrial ranges.

Intensification and spatial homogenization of coastal upwelling under climate change. Wang D, Gouhier TC, Menge BA, and Ganguly AR. (2015). *Nature*, **518**: 390-394. <http://dx.doi.org/10.1038/nature14235>

Geographic Location: California Current System, Canary Current System, Humboldt Current System, and Benguela Current System
Type of Reference: Research Paper

Abstract: The timing and strength of wind-driven coastal upwelling along the eastern margins of major ocean basins regulate the productivity of critical fisheries and marine ecosystems by bringing deep and nutrient-rich waters to the sunlit surface, where photosynthesis can occur. How coastal upwelling regimes might change in a warming climate is therefore a question of vital importance. Although enhanced land-ocean differential heating due to greenhouse warming has been proposed to intensify coastal upwelling by strengthening alongshore winds, analyses of observations and previous climate models have provided little consensus on historical and projected trends in coastal upwelling. Here we show that there are strong and consistent changes in the timing, intensity and spatial heterogeneity of coastal upwelling in response to future warming in most Eastern Boundary Upwelling Systems (EBUSs). An ensemble of climate models shows that by the end of the twenty-first century the upwelling season will start earlier, end later and become more intense at high but not low latitudes. This projected increase in upwelling intensity and duration at high latitudes will result in a substantial reduction of the existing latitudinal variation in coastal upwelling. These patterns are consistent across three of the four EBUSs (Canary, Benguela and Humboldt, but not California). The lack of upwelling intensification and greater uncertainty associated with the California EBUS may reflect regional controls associated with the atmospheric response to climate change. Given the strong linkages between upwelling and marine ecosystems, the projected changes in the intensity, timing and spatial structure of coastal upwelling may influence the geographical distribution of marine biodiversity.

Partial decoupling of primary productivity from upwelling in the California Current system. Renault L, Deutsch C, McWilliams JC, Frenzel H, Lian J, and Colas F (2016). *Nature Geoscience*, **9**: 505-508. <http://dx.doi.org/10.1038/ngeo2722>

Geographic Location: California Current System, Pacific Ocean
Type of Reference: Research Paper



Abstract: Coastal winds and upwelling of deep nutrient-rich water along subtropical eastern boundaries yield some of the ocean's most productive ecosystems. Simple indices of coastal wind strength have been extensively used to estimate the timing and magnitude of biological productivity on seasonal and interannual time scales and underlie the prediction that anthropogenic climate warming will increase the productivity by making coastal winds stronger. The effect of wind patterns on regional net primary productivity is not captured by such indices and is poorly understood. Here we present evidence, using a realistic model of the California Current system and satellite measurements, that the observed slackening of the winds near the coast has little effect on near-shore phytoplankton productivity despite a large reduction in upwelling velocity. On the regional scale the wind drop-off leads to substantially higher production even when the total upwelling rate remains the same. This partial decoupling of productivity from upwelling results from the impact of wind patterns on along shore currents and the eddies they generate. Our results imply that productivity in eastern boundary upwelling systems will be better predicted from indices of the coastal wind that account for its offshore structure.

Sea level rise

Sea level rise provides a physical measure of the ocean's response to climate change. The rise in global sea level is attributed to thermal expansion of ocean water and the melting of mountain glaciers and ice sheets. Coupled atmosphere-ocean perturbations, like El Niño–Southern Oscillation (ENSO), affect sea level in a complex manner. Sea level rise could lead to flooding of low-lying areas, loss of coastal wetlands such as portions of the San Francisco Bay-Delta system, and wave-driven erosion and accretion of cliffs and beaches.

Sea level rise and its coastal impacts. Cazenave A and Cozannet GL (2015). *Earth's Future*, 2(2): 15-34. <http://dx.doi.org/10.1002/2013EF000188>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Global warming in response to accumulation of human-induced greenhouse gases inside the atmosphere has already caused several visible consequences, among them increase of the Earth's mean temperature and ocean heat content, melting of glaciers, and loss of ice from the Greenland and Antarctica ice sheets. Ocean warming and land ice melt in turn are causing sea level to rise. Sea level rise and its impacts on coastal zones have become a question of growing interest in the scientific community, as well as in the media and public. In this review paper, we summarize the most up-to-date knowledge about sea level rise and its causes, highlighting the regional variability that superimposes the global mean rise. We also present sea level projections for the 21st century under different warming scenarios. We next address the issue of the sea level rise impacts. We question whether there is already observational evidence of



coastal impacts of sea level rise and highlight the fact that results differ from one location to another. This suggests that the response of coastal systems to sea level rise is highly dependent on local natural and human settings. We finally show that in spite of remaining uncertainties about future sea levels and related impacts, it becomes possible to provide preliminary assessment of regional impacts of sea level rise.

The effect of the El Niño-Southern Oscillation on U.S. regional and coastal sea level. Hamlington BD, Leben RR, Kim KY, Nerem RS, Atkinson LP, and Thompson PR (2015). *Journal of Geophysical Research: Oceans*, **120**: 3970-3986.
<http://dx.doi.org/10.1002/2014JC010602>

Geographic Location: Pacific Ocean
Type of Reference: Research Paper

Abstract: Although much of the focus on future sea level rise concerns the long-term trend associated with anthropogenic warming, on shorter time scales, internal climate variability can contribute significantly to regional sea level. Such sea level variability should be taken into consideration when planning efforts to mitigate the effects of future sea level change. In this study, we quantify the contribution to regional sea level of the El Niño-Southern Oscillation (ENSO). Through cyclostationary empirical orthogonal function analysis (CSEOF) of the long reconstructed sea level data set and of a set of U.S. tide gauges, two global modes dominated by Pacific Ocean variability are identified and related to ENSO and, by extension, the Pacific Decadal Oscillation. By estimating the combined contribution of these two modes to regional sea level, we find that ENSO can contribute significantly on short time scales, with contributions of up to 20 centimeters (cm) along the west coast of the U.S. The CSEOF decomposition of the long tide gauge records around the U.S. highlights the influence of ENSO on the U.S. east coast. Tandem analyses of both the reconstructed and tide gauge records also examine the utility of the sea level reconstructions for near-coast studies.

Using Time Lapse Cameras to Track Shoreline Change Due to Sea Level Rise: A Research Report from the National Center for Sustainable Transportation. . Shilling F, Waetjen D, Taniguchi K, Grosholz T, Grijalva E, et al. (2017). National Center for Sustainable Transportation. https://ncst.ucdavis.edu/wp-content/uploads/2015/10/NCST-Report-Shilling_SLR_Jan_2017-FINAL.pdf.

Geographic Location: California and Georgia
Type of Reference: Report

Abstract: Shoreline habitats and infrastructure are currently being affected by sea level rise (SLR) and as global temperatures continue to rise, will continue to get worse for millennia. Governments' and individuals' decisions to adapt to SLR could have profound consequences for adjacent ecosystems, transportation systems, and urban settings.



The cost for this adaptation will also increase over time. Natural systems often attenuate impacts of SLR and storms, providing a free and often unrecognized and under-appreciated protective service for shoreline infrastructures. There is no current information available to shoreline agencies on fine-scale and near-term/current changes in shoreline in response to SLR. This project describes a method to monitor shoreline and infrastructure changes in response to SLR using a network of time-lapse cameras. The researchers found that the method was sensitive to vertical changes in sea level of <1 centimeter (cm), roughly equivalent to 1-2 years of SLR under the A1 scenario (i.e., high emissions/business-as-usual). SLR of >20 cm has occurred in the San Francisco Bay and other US coastal areas and is likely to rise by another 30-45 cm by mid-century. This rapid degree of rise means that it is imperative to include planning for infrastructural modifications in current regional and corridor plans. Accurate and timely information about the actual extent of SLR impacts to shorelines will be critical during highway adaptation. The method described is feasible for near-term (1 to 10 years) to long-term application, and can be used for measuring fine-resolution shoreline changes (e.g., degree of inundation, plant cover, and geomorphology) in response to SLR and associated wave action inundation of marshes and infrastructure. The researchers demonstrated the method with networks of cameras in two coastal states (CA and GA), using web-informatics and services to organize photographs that could be combined with related external data (e.g., gauged water levels, moon phases) to create an information mashup. The report discusses how outputs from these techniques could be used to validate models of SLR threats to coastal systems and inform transportation and regulatory decision-making. Finally, they discuss next steps, including using two other, complementary methods for monitoring shorelines: drone-based terrain-mapping and historical, opportunistic and satellite photographs.

Extreme oceanographic forcing and coastal response due to the 2015-2016 El Niño. Barnard PL, Hoover D, Hubbard DM, Snyder A, Ludka BC, et al. (2017). *Nature Communications*, **8**: 14365. <http://dx.doi.org/10.1038/ncomms14365>

Geographic Location: United States West Coast

Type of Reference: Research Paper

Abstract: The El Niño-Southern Oscillation is the dominant mode of interannual climate variability across the Pacific Ocean basin, with influence on the global climate. The two end members of the cycle, El Niño and La Niña, force anomalous oceanographic conditions and coastal response along the Pacific margin, exposing many heavily populated regions to increased coastal flooding and erosion hazards. However, a quantitative record of coastal impacts is spatially limited and temporally restricted to only the most recent events. Here we report on the oceanographic forcing and coastal response of the 2015–2016 El Niño, one of the strongest of the last 145 years. We show that winter wave energy equalled or exceeded measured historical maxima across the US West Coast, corresponding to anomalously large beach erosion across the region. Shorelines in many areas retreated beyond previously measured landward extremes, particularly along the sediment-starved California coast.



Rising Seas in California: An Update on Sea-Level Rise Science. Griggs G, Arvai J, Cayan D, DeConto R, Fox R, et al. (2017). California Ocean Science Trust.

<http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf>.

Geographic Location: California

Type of Reference: Report

From “About this Document” and “Key Findings”: This document was produced by a Working Group of the California Ocean Protection Council Science Advisory Team (OPC-SAT), supported and convened by the California Ocean Science Trust. The State of California Sea-Level Rise Guidance Document, initially adopted in 2010 and updated in 2013, provides guidance to state agencies for incorporating sea-level rise projections into planning, design, permitting, construction, investment and other decisions. Now, the California Ocean Protection Council and the California Natural Resources Agency, in collaboration with the Governor’s Office of Planning and Research, the California Energy Commission, and the California Ocean Science Trust, are updating this statewide guidance to reflect recent advances in ice loss science and projections of sea-level rise. This document, requested by the California Ocean Protection Council and guided by a set of questions from the state Sea- Level Rise Policy Advisory Committee, provides a synthesis of the state of the science on sea-level rise. It provides the scientific foundation for the pending update to the guidance document.

Key findings are:

- Scientific understanding of sea-level rise is advancing at a rapid pace.
- The direction of sea level change is clear.
- The rate of ice loss from the Greenland and Antarctic Ice Sheets is increasing.
- New scientific evidence has highlighted the potential for extreme sea-level rise.
- Probabilities of specific sea-level increases can inform decisions.
- Current policy decisions are shaping our coastal future.
- Waiting for scientific certainty is neither a safe nor prudent option.

Snowpack, snowmelt runoff, lake temperatures and other freshwater impacts

Annual mountain snowpack provides natural storage for water supplies. The water supply from spring and summer snowmelt runoff supports agriculture and industry, growing urban areas, and the ecological health of coastal ocean and riverine environments. Surface water supplies throughout western North America rely on a highly seasonal and variable mountain runoff pattern that is sensitive to climatic variability and change.



The accumulation of snow at high elevations can be affected by warming temperatures. As temperatures warm during the winter months, more precipitation will fall as rain instead of snow. Warmer temperatures will also shift the timing of snowmelt to occur earlier in the spring. As warming and precipitation shifts continue, runoff and streamflow amounts and patterns could be affected, impacting water supplies.

Morphometry and average temperature affect lake stratification responses to climate change: Lake stratification responses to climate. Kraemer BM, Anneville O, Chandra S, Dix M, Kuusisto E, et al. (2015). *Geophysical Research Letters*, **42**(12): 4981-4988. <http://dx.doi.org/10.1002/2015GL064097>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Climate change is affecting lake stratification with consequences for water quality and the benefits that lakes provide to society. Here we use long-term temperature data (1970–2010) from 26 lakes around the world to show that climate change has altered lake stratification globally and that the magnitudes of lake stratification changes are primarily controlled by lake morphometry (mean depth, surface area, and volume) and mean lake temperature. Deep lakes and lakes with high average temperatures have experienced the largest changes in lake stratification even though their surface temperatures tend to be warming more slowly. These results confirm that the nonlinear relationship between water density and water temperature, and the strong dependence of lake stratification on lake morphometry makes lake temperature trends relatively poor predictors of lake stratification trends.

Comparing historic and future climate and hydrology for California's watersheds using the Basin Characterization Model. Thorne JH, Boynton RM, Flint LE, and Flint AL (2015). *Ecosphere*, **6**(2): 24. <http://dx.doi.org/10.1890/ES14-00300.1>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Process-based models that link climate and hydrology permit improved assessments of climate change impacts among watersheds. We used the Basin Characterization Model (BCM), a regional water balance model to (1) ask what is the magnitude of historical and projected future change in the hydrology of California's watersheds; (2) test the spatial congruence of watersheds with the most historical and future hydrologic change; and (3) identify watersheds with high levels of hydrologic change under drier and wetter future climates. We assessed change for 5135 watersheds over a 60-year historical period and compared it to 90-year future projections. Watershed change was analyzed for climatic water deficit, April 1st snowpack, recharge, and runoff. Watersheds were ranked by change for the historical



and two future scenarios. We developed a normalized index of hydrologic change that combined the four variables, and identified which watersheds show the most spatial congruence of large historical change and continued change under the two futures. Of the top 20% of all watersheds (1028), 591 in the Sierra Nevada Mountains and Northwestern ecoregions have high spatial congruence across all time periods. Among watersheds where change accelerates in the future, but not historically, a majority are congruent between both climate models, predominantly in the Sierra Nevada, Cascade Ranges and the Northwestern ecoregions. This congruence of impacts in watersheds under drier or wetter scenarios is driven by snowpack, but in areas with low snowpack, hydrologic change varied spatially depending on projected precipitation and temperature, with 151 watersheds in Northwestern California showing high levels of drying under the drier scenario, while 103 watersheds in Central western and Southwestern California show increasing hydrologic activity under the wetter scenario. In some regions, the loss of snowpack allows the cycle of runoff and recharge to function without delay represented by springtime snow melt, causing these watersheds to become more immediately hydrologically responsive to changing climate. The study also found watersheds with low rainfall that have already passed through their highest response to changing climate, and show less future change. The methods used here can also be used to identify watersheds resilient to changing climate.

Sensitivity of intermittent streams to climate variations in the USA. Eng K, Wolock DM, and Dettinger MD (2015). *River Research and Applications*, **32**(5): 885-895. <http://dx.doi.org/10.1002/rra.2939>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: There is a great deal of interest in the literature on streamflow changes caused by climate change because of the potential negative effects on aquatic biota and water supplies. Most previous studies have primarily focused on perennial streams, and there have been only a few studies examining the effect of climate variability on intermittent streams. Our objectives in this study were to (1) identify regions of similar zero-flow behaviour and (2) evaluate the sensitivity of intermittent streams to historical variability in climate in the USA. This study was carried out at 265 intermittent streams by evaluating (1) correlations among time series of flow metrics (number of zero-flow events, the average of the central 50% and largest 10% of flows) with climate (magnitudes, durations and intensity) and (2) decadal changes in the seasonality and long-term trends of these flow metrics. Results identified five distinct seasonality patterns in the zero-flow events. In addition, strong associations between the low-flow metrics and historical changes in climate were found. The decadal analysis suggested no significant seasonal shifts or decade-to-decade trends in the low-flow metrics. The lack of trends or changes in seasonality is likely due to unchanged long-term patterns in precipitation over the time period examined.



Climate change impacts on lake thermodynamics and ecosystem vulnerabilities.

Sahoo GB, Forrest AL, Schladow SG, Reuter JE, Coats R, and Dettinger M (2015). *Limnology and Oceanography*, **61**: 496-507. <http://dx.doi.org/10.1002/lno.10228>

Geographic Location: Lake Tahoe, California

Type of Reference: Research Paper

Abstract: Using water column temperature records collected since 1968, we analyzed the impacts of climate change on thermal properties, stability intensity, length of stratification, and deep mixing dynamics of Lake Tahoe using a modified stability index (SI). This new SI is easier to produce and is a more informative measure of deep lake stability than commonly used stability indices. The annual average SI increased at 16.62 kilograms per square meter (kg/m^2)/decade although the summer (May–October) average SI increased at a higher rate (25.42 kg/m^2 /decade) during the period 1968–2014. This resulted in the lengthening of the stratification season by approximately 24 days. We simulated the lake thermal structure over a future 100 year period using a lake hydrodynamic model driven by statistically downscaled outputs of the Geophysical Fluid Dynamics Laboratory Model (GFDL) for two different greenhouse gas emission scenarios (the A2 in which greenhouse-gas emissions increase rapidly throughout the 21st Century, and the B1 in which emissions slow and then level off by the late 21st Century). The results suggest a continuation and intensification of the already observed trends. The length of stratification duration and the annual average lake stability are projected to increase by 38 d and 12 d and 30.25 kg/m^2 /decade and 8.66 kg/m^2 /decade, respectively for GFDLA2 and GFDLB1, respectively during 2014–2098. The consequences of this change bear the hallmarks of climate change induced lake warming and possible exacerbation of existing water quality, quantity and ecosystem changes. The developed methodology could be extended and applied to other lakes as a tool to predict changes in stratification and mixing dynamics.

Rapid and highly variable warming of lake surface waters around the globe.

O'Reilly CM, Sharma S, Gray DK, Hampton SE, Read JS, et al. (2015). *Geophysical Research Letters*, **42**(24): 10773-10781. <http://dx.doi.org/10.1002/2015GL066235>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: In this first worldwide synthesis of in situ and satellite-derived lake data, we find that lake summer surface water temperatures rose rapidly (global mean = 0.34°C/decade) between 1985 and 2009. Our analyses show that surface water warming rates are dependent on combinations of climate and local characteristics, rather than just lake location, leading to the counterintuitive result that regional consistency in lake warming is the exception, rather than the rule. The most rapidly warming lakes are widely geographically distributed, and their warming is associated with interactions among different climatic factors—from seasonally ice-covered lakes in areas where temperature and solar radiation are increasing while cloud



cover is diminishing ($0.72^{\circ}\text{C decade}^{-1}$) to ice-free lakes experiencing increases in air temperature and solar radiation ($0.53^{\circ}\text{C decade}^{-1}$). The pervasive and rapid warming observed here signals the urgent need to incorporate climate impacts into vulnerability assessments and adaptation efforts for lakes.

Climate change and the delta. Dettinger MD, Anderson J, Anderson M, Brown L, Cayan DR, and Maurer EP (2016). *San Francisco Estuary and Watershed Science*, 14(3). <https://doi.org/10.15447/sfews.2016v14iss3art5>.

Geographic Location: Sacramento–San Joaquin Delta, California

Type of Reference: Review Article

Abstract: Anthropogenic climate change amounts to a rapidly approaching, “new” stressor in the Sacramento–San Joaquin Delta system. In response to California’s extreme natural hydroclimatic variability, complex water-management systems have been developed, even as the Delta’s natural ecosystems have been largely devastated. Climate change is projected to challenge these management and ecological systems in different ways that are characterized by different levels of uncertainty. For example, there is high certainty that climate will warm by about 2°C more (than late-20th-century averages) by mid-century and about 4°C by end of century, if greenhouse-gas emissions continue their current rates of acceleration. Future precipitation changes are much less certain, with as many climate models projecting wetter conditions as drier. However, the same projections agree that precipitation will be more intense when storms do arrive, even as more dry days will separate storms. Warmer temperatures will likely enhance evaporative demands and raise water temperatures. Consequently, climate change is projected to yield both more extreme flood risks and greater drought risks. Sea level rise (SLR) during the 20th century was about 22 cm, and is projected to increase by at least 3-fold this century. SLR together with land subsidence threatens the Delta with greater vulnerabilities to inundation and salinity intrusion. Effects on the Delta ecosystem that are traceable to warming include SLR, reduced snowpack, earlier snowmelt and larger storm-driven streamflows, warmer and longer summers, warmer summer water temperatures, and water-quality changes. These changes and their uncertainties will challenge the operations of water projects and uses throughout the Delta’s watershed and delivery areas. Although the effects of climate change on Delta ecosystems may be profound, the end results are difficult to predict, except that native species will fare worse than invaders. Successful preparation for the coming changes will require greater integration of monitoring, modeling, and decision making across time, variables, and space than has been historically normal.

Multi-century evaluation of Sierra Nevada snowpack. Belmecheri S, Babst F, Wahl ER, Stahle DW, and Trouet V. (2016). *Nature Climate Change*, 6(1): 2-3. <http://dx.doi.org/10.1038/nclimate2809>



Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

From Abstract: California is currently experiencing a record-setting drought that started in 2012 and recently culminated in the first ever mandatory state-wide water restriction. The snowpack conditions in the Sierra Nevada mountains present an ominous sign of the severity of this drought: the 1 April 2015 snow water equivalent (SWE) was at only 5% of its historical average. In the Mediterranean climate of California, with 80% of the precipitation occurring during winter months, Sierra Nevada snowpack plays a critical role in replenishing the state's water reservoirs and provides 30% of its water supply. As a result, a multi-year and severe snowpack decline can acutely impact human and natural systems, including urban and agricultural water supplies, hydroelectric power and wildfire risk.

Interlinking climate change with water-energy-food nexus and related ecosystem processes in California case studies. Liu Q (2016). *Ecological Processes*, 5:14.
<http://dx.doi.org/10.1186/s13717-016-0058-0>

Geographic Location: California

Type of Reference: Review Article

Abstract: Global climate change creates critical challenges with increasing temperature, reducing snowpack, and changing precipitation for water, energy, and food, as well as ecosystem processes at regional scales. Ecosystem services provide life support, goods, and natural resources from water, energy, and food, as well as the environments. There are knowledge gaps from the lack of conceptual framework and practices to interlink major climate change drivers of water resources with water-energy-food nexus and related ecosystem processes. This paper provided an overview of research background, developed a conceptual framework to bridge these knowledge gaps, summarized California case studies for practices in cross sector ecosystem services, and identified future research needs. In this conceptual framework, climate change drivers of changing temperature, snowpack, and precipitation are interlinked with life cycles in water, energy, food, and related key elements in ecosystem processes. Case studies in California indicated climate change affected variation in increasing temperature and changing hydrology at the regional scales. A large variation in average energy intensity values was also estimated from ground water and federal, state, and local water supplies both within each hydrological region and among the ten hydrological regions in California. The increased regional temperature, changes in snowpack and precipitation, and increased water stresses from drought can reduce ecosystem services and affect the water and energy nexus and agricultural food production, as well as fish and wildlife habitats in the Sacramento-San Joaquin Delta (Delta) and Central Valley watersheds. Regional decisions and practices in integrated management of water, energy, food, and related ecosystem processes are essential to adapt and mitigate global climate change impacts at the regional scales. Science and policy support for interdisciplinary research are critical to develop the database and



tools for comprehensive analysis to fill knowledge gaps and address ecosystem service complexity, the related natural resource investment, and integrated planning needs.

Anthropogenic warming impacts on California snowpack during drought. Berg N and Hall A (2017). *Geophysical Research Letters*, **44**(5): 2511. <http://dx.doi.org/10.1002/2016GL072104>

Geographic Location: Sierra Nevada, California
Type of Reference: Research Paper

Key Points: Sierra Nevada climate and snowpack is simulated during the period of extreme drought from 2011 to 2015 and compared to an identical simulation except for the removal of the twentieth century anthropogenic warming. Anthropogenic warming reduced average snowpack levels by 25%, with middle-to-low elevations experiencing reductions between 26 and 43%. In terms of event frequency, return periods associated with anomalies in 4 year 1 April snow water equivalent are estimated to have doubled, and possibly quadrupled, due to past warming. We also estimate effects of future anthropogenic warmth on snowpack during a drought similar to that of 2011–2015. Further snowpack declines of 60–85% are expected, depending on emissions scenario. The return periods associated with future snowpack levels are estimated to range from millennia to much longer. Therefore, past human emissions of greenhouse gases are already negatively impacting statewide water resources during drought, and much more severe impacts are likely to be inevitable.

The geography of glaciers and perennial snowfields in the American West. Fountain AG, Glenn B, and Basagic IV HJ (2017). *Arctic, Antarctic, and Alpine Research*, **49**(3): 391-410. <http://dx.doi.org/10.1657/AAAR0017-003>

Geographic Location: Western United States
Type of Reference: Research Paper

Abstract: A comprehensive mid-20th century inventory of glaciers and perennial snowfields (G&PS) was compiled for the American West, west of the 100° meridian. The inventory was derived from U.S. Geological Survey 1:24,000 topographic maps based on aerial photographs acquired during 35 years, 1955–1990, of which the first 20 years or more was a cool period with little glacier change. The mapped features were filtered for those greater than 0.01 kilometers (km)². Results show that 5036 G&PS (672 km², 14 km³) populate eight states, of which about 1276 (554 km², 12 km³) are glaciers. Uncertainty is estimated at ±9% for area and ±20% for volume. Two populations of G&PS were identified based on air temperature and precipitation. The larger is found in a maritime climate of the Pacific Northwest, characterized by warm winter air temperatures and high winter precipitation (~2100 mm). The other population is continental in climate, characterized by cold winter air temperatures, relatively low



winter precipitation (~880 mm), and located at higher elevations elsewhere. The G&PS in the Pacific Northwest, especially in the Olympic Mountains, are particularly vulnerable to warming winter air temperatures that will change the phase of winter precipitation from snow to rain, further accelerating glacier shrinkage in the future. Comparison with a recent inventory suggests that the total G&PS area in the American West may have decreased by as much as 39% since the mid-20th century.

Winter snow level rise in the northern Sierra Nevada from 2008 to 2017.

Hatchett BJ, B Daudert, CB Garner, NS Oakley AE Putnam and AB White (2017).

Water, 9(11): 899. <http://dx.doi.org/10.3390/w9110899>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Abstract: The partitioning of precipitation into frozen and liquid components influences snow-derived water resources and flood hazards in mountain environments. We used a 915-MHz Doppler radar wind profiler upstream of the northern Sierra Nevada to estimate the hourly elevation where snow melts to rain, or the snow level, during winter (December–February) precipitation events spanning water years (WY) 2008–2017. During this ten-year period, a Mann-Kendall test indicated a significant ($p < 0.001$) positive trend in snow level with a Thiel-Sen slope of 72 meters year⁻¹. We estimated total precipitation falling as snow (snow fraction) between WY1951 and 2017 using nine daily mid-elevation (1200–2000 meters) climate stations and two hourly stations spanning WY2008–2017. The climate-station-based snow fraction estimates agreed well with snow-level radar values ($R^2 = 0.95$, $p < 0.01$), indicating that snow fractions represent a reasonable method to estimate changes in frozen precipitation. Snow fraction significantly ($p < 0.001$) declined during WY2008–2017 at a rate of 0.035 (3.5%) year⁻¹. Single-point correlations between detrended snow fraction and sea-surface temperatures (SST) suggested that positive SST anomalies along the California coast favor liquid phase precipitation during winter. Reanalysis-derived integrated moisture transported upstream of the northern Sierra Nevada was negatively correlated with snow fraction ($R^2 = 0.90$, $p < 0.01$), with atmospheric rivers representing the likely circulation mechanism producing low-snow-fraction storms.



Tahoe: State of the Lake Reports (2007 – 2017). University of California, Davis. Tahoe Environmental Research Center. Available at <http://terc.ucdavis.edu/stateofthelake/>

Geographic Location: Lake Tahoe, California

Type of Reference: Academic report

From Executive Summary of 2017 Report: This annual Tahoe: State of the Lake Report presents data from 2016 in the context of the long- term record. While we report on the data collected as part of our ongoing, decades-long measurement programs, we also include sections summarizing current research that is being driven by the important questions of the day. These include: the causes of the increasing levels of filamentous algae seen on the shoreline; the health of Lake Tahoe’s forests in response to drought; climate change and its impacts on the lake physics and the entire lake ecosystem; the driving force behind the variability of water quality around the lake’s nearshore regions; a first look at what is happening in the very deepest parts of the lake; and the threat of invasive species spread by in-lake boating activities.



Impacts of Climate Change on Biological Systems

Climate has wide-ranging impacts on biological systems. Plants and animals reproduce and survive within specific ranges often defined by climatic and environmental conditions. Hence, changes in climate—particularly temperature and moisture—can have broad effects on organisms at all levels.

There is a growing body of evidence of the effects of climate change on biological systems around the globe, including changes in the timing of life cycle events (phenology), shifts in the elevation or latitude of plant and animal habitat ranges, and changes in the population abundance of certain species. Changes in climate add to the ecosystem stresses exerted by non-climate factors (such as habitat fragmentation and pollution). Individual species responses can impact other species and the ecosystem, as they may for example disrupt predator-prey and other ecological relationships, alter ecological community composition, and interfere with ecosystem functioning. This chapter lists publications on impacts on humans, animals and plants. Impacts on humans are first listed. Impacts on animals are categorized as follows: range shifts; body size changes; migration time; and population abundance and ecological interactions. Impacts on plants are categorized as follows: agricultural crops; vegetation; wildfires; and harmful algal blooms (although the latter are colonies of algae and/or plant-like bacteria, rather than plants).

Impacts on humans

Increases in the frequency and duration of heat waves are expected to result in a greater public health burden. In addition to the increased risk of deaths and illnesses from exposures to heat, other impacts on human health include vector-borne diseases; death, disease and injury from storms, floods and fires; reduced water quality and availability; and increased morbidity and mortality associated with air pollution. Research has also focused on factors affecting vulnerability to the health impacts of climate change, including how these could lead to disproportionate impacts on certain populations.

Heat-related morbidity and mortality

Heat-related illness is a broad spectrum of disease, from mild heat cramps to severe, life-threatening heat stroke, to death. Heat waves have long been known to cause illnesses and deaths — outcomes which are largely preventable. Recent California studies suggest increased health risk not only with extreme heat, but also with increasing ambient temperatures. Furthermore, adverse health effects not previously recognized to be affected by heat, such as stillbirth, pre-term delivery and mental health



outcomes, have been recently reported. A growing body of literature has identified individual and population characteristics that increase vulnerability to the heat-related health impacts of climate change.

The mental health outcomes of drought: A systematic review and causal process diagram. Vins H, Bell J, Saha S, and Hess JJ (2015). *International Journal of Environmental Research and Public Health*, **12**(10): 13251-13275.
<http://dx.doi.org/10.3390/ijerph121013251>

Geographic Location: United States

Type of Reference: Review Article

Description: Little is understood about the long term, indirect health consequences of drought (a period of abnormally dry weather). In particular, the implications of drought for mental health via pathways such as loss of livelihood, diminished social support, and rupture of place bonds have not been extensively studied, leaving a knowledge gap for practitioners and researchers alike. A systematic review of literature was performed to examine the mental health effects of drought. The systematic review results were synthesized to create a causal process diagram that illustrates the pathways linking drought effects to mental health outcomes. Eighty-two articles using a variety of methods in different contexts were gathered from the systematic review. The pathways in the causal process diagram with greatest support in the literature are those focusing on the economic and migratory effects of drought. The diagram highlights the complexity of the relationships between drought and mental health, including the multiple ways that factors can interact and lead to various outcomes. The systematic review and resulting causal process diagram can be used in both practice and theory, including prevention planning, public health programming, vulnerability and risk assessment, and research question guidance. The use of a causal process diagram provides a much needed avenue for integrating the findings of diverse research to further the understanding of the mental health implications of drought.

Mortality during a large-scale heat wave by place, demographic group, internal and external causes of death, and building climate zone. Joe L, Hoshiko S, Dobraca D, Jackson R, Smorodinsky S, et al. (2016). *International Journal of Environmental Research and Public Health*, **13**(3): E299.
<http://dx.doi.org/10.3390/ijerph13030299>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Mortality increases during periods of elevated heat. Identification of vulnerable subgroups by demographics, causes of death, and geographic regions, including deaths occurring at home, is needed to inform public health prevention efforts.



We calculated mortality relative risks (RRs) and excess deaths associated with a large-scale California heat wave in 2006, comparing deaths during the heat wave with reference days. For total (all-cause) and at-home mortality, we examined risks by demographic factors, internal and external causes of death, and building climate zones. During the heat wave, 582 excess deaths occurred, a 5% increase over expected (RR = 1.05, 95% confidence interval (CI) 1.03–1.08). Sixty-six percent of excess deaths were at home (RR = 1.12, CI 1.07–1.16). Total mortality risk was higher among those aged 35–44 years than ≥ 65 , and among Hispanics than whites. Deaths from external causes increased more sharply (RR = 1.18, CI 1.10–1.27) than from internal causes (RR = 1.04, CI 1.02–1.07). Geographically, risk varied by building climate zone; the highest risks of at-home death occurred in the northernmost coastal zone (RR = 1.58, CI 1.01–2.48) and the southernmost zone of California's Central Valley (RR = 1.43, CI 1.21–1.68). Heat wave mortality risk varied across subpopulations, and some patterns of vulnerability differed from those previously identified. Public health efforts should also address at-home mortality, non-elderly adults, external causes, and at-risk geographic regions.

Characterizing occupational heat-related mortality in the United States, 2000-2010: An analysis using the census of fatal occupational injuries database.

Gubernot DM, Anderson CG, and Hunting KL (2016). *American Journal of Industrial Medicine*, **58**(2): 203-211. <http://dx.doi.org/10.1002/ajim.22381>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: Occupational heat-related mortality is not well studied and risk factors remain largely unknown. This paper describes the epidemiological characteristics of heat-related deaths among workers in the US 2000-2010. Fatality data were obtained at the Bureau of Labor Statistics from the confidential on-site Census of Fatal Occupational Injuries database. Fatality rates and risk ratios with 95% confidence intervals were calculated by year, sex, age group, ethnicity, race, state, and industry. Between 2000 and 2010, 359 occupational heat-related deaths were identified in the U.S., for a yearly average fatality rate of 0.22 per 1 million workers. Highest rates were found among Hispanics, men, the agriculture and construction industries, the state of Mississippi, and very small establishments. This study provides the first comprehensive national profile of heat-related deaths in the U.S. workplace. Prevention efforts should be directed at small businesses and at industries and individuals with the highest risk.

High ambient temperature exposure increases the risk of stillbirth in California.

Basu R, Sarovar V and Malig B (2016). *American Journal of Epidemiology*, **183**(10): 894-901. <http://dx.doi.org/10.1093/aje/kwv295>



Geographic Location: California
Type of Reference: Research Paper

Abstract: Recent studies have linked elevated apparent temperatures with adverse birth outcomes, such as preterm delivery, but other birth outcomes have not been well studied. We examined 8,510 fetal deaths (≥ 20 weeks' gestation) to estimate their association with mean apparent temperature, a combination of temperature and humidity, during the warm season in California (May-October) from 1999 to 2009. Mothers whose residential zip codes were within 10 kilometers of a meteorological monitor were included. Meteorological data were provided by the California Irrigation Management Information System, the US Environmental Protection Agency, and the National Climatic Data Center, while the California Department of Public Health provided stillbirth data. Using a time-stratified case-crossover study design, we found a 10.4% change (95% confidence interval: 4.4, 16.8) in risk of stillbirth for every 10° Fahrenheit (F) (5.6°Celsius) increase in apparent temperature (cumulative average of lags 2-6 days). Risk varied by maternal race/ethnicity and was greater for younger mothers, less educated mothers, and male fetuses. The highest risks were observed during gestational weeks 20-25 and 31-33. No associations were found during the cold season (November-April), and the observed associations were independent of air pollutants. This study adds to the growing body of literature identifying pregnant women and their fetuses as subgroups vulnerable to heat exposure.

Environment, global climate change, and cardiopulmonary health. Bayram H, Bauer AK, Abdalati W, Carlsten C, Pinkerton KE, et al. (2017). *American Journal of Respiratory and Critical Care Medicine*, **195**(6):718-724.
<http://dx.doi.org/10.1164/rccm.201604-0687PP>.

Geographic Location: Global
Type of Reference: Review Article

Abstract: There is widespread agreement among scientists that climate change, primarily due to greenhouse gas (GHG) production from human activities, is causing significant global health impacts. The focus of this Pulmonary Perspective is to highlight emerging evidence for cardio-respiratory health impacts related to climate change, and to suggest possible strategies for individual and collective responses to this threat. Adaptation and mitigation strategies, along with co-benefits of these actions, are also discussed. The association between heat stress and cardiopulmonary mortality is well established. Hot and drier climates are associated with increased land degradation and desertification, impacting food production and particulate matter air pollution worldwide. Warmer temperatures also increase levels of ozone and combustion particles, and extend the growing season of allergenic plants and fungi. Extreme weather (e.g., hurricanes, cyclones and floods) cause acute injuries and associated mortality and morbidity, but also longer term impacts of increased gastro-intestinal illness, degraded housing, and increased levels of indoor microbial growth that can contribute to



pulmonary disease. While these impacts are daunting, coping with climate change also offers opportunities for public health. Reductions in GHG emissions reduce other air pollutants. Climate-driven adaptation in our food and water distribution systems could lead to more equitable distribution of these eco-necessities. Improved urban design and transportation could improve physical activity levels and make today's urban environments more hospitable. The positive outcomes of California's multi-pronged climate change mitigation policies provide one example in which such strategies have limited GHG emissions, and shifted energy use to more sustainable sources.

Drought and the risk of hospital admissions and mortality in older adults in western USA from 2000 to 2013: A retrospective study. Berman JD, Ebisu K, Peng RD, Dominici F, and Bell ML (2017). *The Lancet Planetary Health*, 1(1): e17-e25. [http://dx.doi.org/10.1016/S2542-5196\(17\)30002-5](http://dx.doi.org/10.1016/S2542-5196(17)30002-5).

Geographic Location: Western United States

Type of Reference: Research Paper

Abstract: *Background:* Occurrence, severity, and geographic extent of droughts are anticipated to increase under climate change, but the health consequences of drought conditions are unknown. We estimate risks of cardiovascular-related and respiratory-related hospital admission and mortality associated with drought conditions for the elderly population in western USA. *Methods:* For this retrospective study, we analyzed the 2000 to 2013 data from the US Drought Monitor for 618 counties in the western USA to identify full drought periods, non-drought periods, and worsening drought periods stratified by low severity and high severity. We used Medicare claims made between Jan 1, 2000, and Dec 31, 2013, to calculate daily rates of cardiovascular admissions, respiratory admissions, and deaths among adults aged 65 years or older. Using a two-stage hierarchical model, we estimated the percentage change in health risks when comparing drought with non-drought period days, controlling for daily weather and seasonal trends. *Findings:* On average, 2.1 million days were classified as non-drought periods and 0.6 million days were classified as drought periods. Compared with non-drought periods, respiratory admissions significantly decreased by -1.99% (95% posterior interval -3.56 to -0.38) during the full drought period, but not during worsening drought conditions. Mortality risk significantly increased by 1.55% (0.17 to 2.95) during the high-severity worsening drought period, but not the full drought or low-severity worsening drought periods. Cardiovascular admissions did not differ significantly during either full drought or worsening drought periods. In counties where drought occurred less frequently, we found risks for cardiovascular disease and mortality to increase during worsening drought conditions. *Interpretation:* Drought conditions increased risk of mortality during high-severity worsening drought, but decreased the risk of respiratory admissions during full drought periods among adults aged 65 years and older. Counties that previously had fewer drought events show larger risk for mortality and cardiovascular disease. This research describes an understudied environmental association with global health significance. *Funding:* The



Yale Institute of Biospheric Studies, the National Institute of Environmental Health Sciences, the US Environmental Protection Agency.

The impact of maternal factors on the association between temperature and preterm delivery. Basu R, Chen H, Li DK, and Avalos LA (2017). *Environmental Research*, **154**: 109-114. <http://dx.doi.org/10.1016/j.envres.2016.12.017>

Geographic Location: Northern California

Type of Reference: Research Paper

Abstract: *Background:* Few studies have examined maternal modifiers of temperature and adverse birth outcomes because of lack of data. We assessed the relationship between apparent temperature, preterm delivery (PTD) and maternal demographics, medical and mental health conditions, and behaviors. *Methods:* A time-stratified case-crossover analysis was conducted using 14,466 women who had a PTD (20 to less than 37 gestational weeks) from 1995 to 2009 using medical records from a large health maintenance organization in Northern California. Effect modifiers considered by stratification included several maternal factors: age, race/ethnicity, depression, hypertension, diabetes, smoking, alcohol use, pre-pregnancy body mass index, and Medicaid status. Apparent temperature data for women who had a monitor located within 20 kilometers of their residential zip codes were included. All analyses were stratified by warm (May 1 through October 31) and cold (November 1 through April 30) seasons. *Results:* For every 10°Fahrenheit (5.6°Celsius) increase in average cumulative weekly apparent temperature (lag06), a greater risk was observed for births occurring during the warm season (11.63%; 95% confidence interval: 4.08, 19.72%) compared to the cold season (6.18%; -2.96, 16.18%), especially for mothers who were younger, Black, Hispanic, underweight, smoked or consumed alcohol during pregnancy, or had pre-existing/gestational hypertension, diabetes, or pre-eclampsia. *Conclusions:* Our findings suggest that warmer apparent temperatures exacerbate the risk of PTD, particularly for subgroups of more vulnerable women.

Protecting the Health and Well-Being of Communities in a Changing Climate: Proceedings of a Workshop – In Brief. National Academies of Sciences, Engineering, and Medicine (2017). Washington, DC: The National Academies Press. <http://dx.doi.org/10.17226/24797>.

Geographic Location: United States

Type of Reference: Report

Description: A March 13, 2017 workshop explored the implications of climate change for population health and the potential mitigation and adaptation strategies for public health, environmental health, health care and other stakeholders. The workshop also explored a range of perspectives from local government, civil society organizations, and



health care organizations, and showcased practical examples of strategies to address climate effects on population health. This brief proceedings of a workshop was prepared by designated rapporteurs in accordance with institutional guidelines as a factual summation of the sessions discussed. The one-day public workshop was co-hosted by the Roundtable on Environmental Health Sciences, Research, and Medicine and the Roundtable on Population Health Improvement, two convening activities of the National Academies of Sciences, Engineering and Medicine.

Examining the association between temperature and emergency room visits for mental health-related outcomes in California. Basu R, Gavin L, Pearson D, Ebisu K, and Malig B (2018). *American Journal of Epidemiology*, **187**(4): 726-735.
<http://dx.doi.org/10.1093/aje/kwx295>.

Geographic Location: California

Type of Reference: Research Paper

Description: Temperature and morbidity has been explored previously. However, the association between temperature and mental health-related outcomes, including violence and self-harm, remains relatively unexamined. We obtained daily counts of mental health-related emergency room visits involving injuries with external cause from the California Office of Statewide Health Planning and Development from 16 California climate zones from 2005 to 2013, and combined them with data on mean apparent temperature, a combination of temperature and humidity. Using Poisson regression models, we estimated climate zone-level associations, then used random-effects meta-analyses to produce overall estimates. Analyses were stratified by season (warm: May-October; cold: November-April), race/ethnicity, and age. A 10-degree Fahrenheit increase in same-day mean apparent temperature was associated with a 4.8% (95% confidence interval, 3.6-6.0%), 5.8% (4.5-7.1%), and 7.9% (7.3-8.4%) increase in visits for mental health disorders, self-injury/suicide, and intentional injury/homicide, respectively, during the warm season. High temperatures during the cold season were also positively associated with these outcomes. Variations were observed by race/ethnicity, age group, and sex, with Hispanics, Whites, 6-18 year olds, and females at greatest risk for most outcomes. Increasing mean apparent temperature was found to have acute associations with mental health outcomes and intentional injuries, and warrants further studies in other locations.

Impact of drought on crime in California: A synthetic control approach. Goin DE, Rudolph KE, and Ahern J (2017). *PLoS ONE*, **12**(10): e0185629.
<http://dx.doi.org/10.1371/journal.pone.0185629>.

Geographic Location: California

Type of Reference: Research Paper



Abstract: Climate and weather have been linked to criminal activity. The connection between climatological conditions and crime is of growing importance as we seek to understand the societal implications of climate change. This study describes the mechanisms theorized to link annual variations in climate to crime in California and examines the effect of drought on statewide crime rates from 2011–2015. California has suffered severe drought since 2011, resulting in intensely dry winters and several of the hottest days on record. It is likely that the drought increased economic stress and shifted routine activities of the population, potentially increasing the likelihood of crime. We used a synthetic control method to estimate the impact of California’s drought on both property and violent crimes. We found a significant increase in property crimes during the drought, but no effect on violent crimes. This result was robust to several sensitivity analyses, including a negative control.

The *Lancet* Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. Watts N, Amann M, Ayab-Karlsson S, Belesova K, Bouley T, et al. (2018). *The Lancet*, **391**(10120): 581-630.
[http://dx.doi.org/10.1016/S0140-6736\(17\)32464-9](http://dx.doi.org/10.1016/S0140-6736(17)32464-9)

Geographic Location: Global

Type of Reference: Review Article

Abstract: The Lancet Countdown tracks progress on health and climate change and provides an independent assessment of the health effects of climate change, the implementation of the Paris Agreement, and the health implications of these actions. It follows on from the work of the 2015 Lancet Commission on Health and Climate Change, which concluded that anthropogenic climate change threatens to undermine the past 50 years of gains in public health, and conversely, that a comprehensive response to climate change could be “the greatest global health opportunity of the 21st century”. The Lancet Countdown is a collaboration between 24 academic institutions and intergovernmental organizations based in every continent and with representation from a wide range of disciplines. The collaboration includes climate scientists, ecologists, economists, engineers, experts in energy, food, and transport systems, geographers, mathematicians, social and political scientists, public health professionals, and doctors. It reports annual indicators across five sections: climate change impacts, exposures, and vulnerability; adaptation planning and resilience for health; mitigation actions and health co-benefits; economics and finance; and public and political engagement.

Health impacts of wildfire smoke exposure

Throughout the western United States, large wildfires have increased in number and acreage burned over recent decades. Increased spring and summer temperatures and earlier snowmelt have been associated with increased large wildfire activity. Wildfires severely impact air quality both locally and in areas downwind of the fire. Exposures to



wildfire smoke, which contains particulate matter, carbon monoxide and various volatile organic compounds, have been associated with general respiratory illnesses and exacerbations of asthma and chronic obstructive pulmonary disease.

Valuing morbidity effects of wildfire smoke exposure from the 2007 Southern California wildfires. Kochi I, Champ PA, Loomis JB, and Donovan GH (2016). *Journal of Forest Economics*, **25**: 29-54. <http://dx.doi.org/10.1016/j.jfe.2016.07.002>.

Geographic Location: Southern California

Type of Reference: Research Paper

Abstract: The area burned by Southern California wildfires has increased in recent decades, with implications for human health, infrastructure, and ecosystem management. Meteorology and fuel structure are universally recognized controllers of wildfire, but their relative importance, and hence the efficacy of abatement and suppression efforts, remains controversial. Southern California's wildfires can be partitioned by meteorology: fires typically occur either during Santa Ana winds (SA fires) in October through April, or warm and dry periods in June through September (non-SA fires). Previous work has not quantitatively distinguished between these fire regimes when assessing economic impacts or climate change influence. Here we separate five decades of fire perimeters into those coinciding with and without SA winds. The two fire types contributed almost equally to burned area, yet SA fires were responsible for 80% of cumulative 1990–2009 economic losses (\$3.1 Billion). The damage disparity was driven by fire characteristics: SA fires spread three times faster, occurred closer to urban areas, and burned into areas with greater housing values. Non-SA fires were comparatively more sensitive to age-dependent fuels, often occurred in higher elevation forests, lasted for extended periods, and accounted for 70% of total suppression costs. An improved distinction of fire type has implications for future projections and management. The area burned in non-SA fires is projected to increase 77% ($\pm 43\%$) by the mid-21st century with warmer and drier summers, and the SA area burned is projected to increase 64% ($\pm 76\%$), underscoring the need to evaluate the allocation and effectiveness of suppression investments.

Critical review of health impacts of wildfire smoke exposure. Reid CE, Brauer M, Johnston FH, Jerrett M, Balmes JR, and Elliott CT (2016). *Environmental Health Perspectives*, **124**(9): 1334-1343. <http://dx.doi.org/10.1289/ehp.1409277>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: *Background:* Wildfire activity is predicted to increase in many parts of the world due to changes in temperature and precipitation patterns from global climate change. Wildfire smoke contains numerous hazardous air pollutants and many studies



have documented population health effects from this exposure. *Objectives:* We aimed to assess the evidence of health effects from exposure to wildfire smoke and to identify susceptible populations. *Methods:* We reviewed the scientific literature for studies of wildfire smoke exposure on mortality and on respiratory, cardiovascular, mental, and perinatal health. Within those reviewed papers deemed to have minimal risk of bias, we assessed the coherence and consistency of findings. *Discussion:* Consistent evidence documents associations between wildfire smoke exposure and general respiratory health effects, specifically exacerbations of asthma and chronic obstructive pulmonary disease. Growing evidence suggests associations with increased risk of respiratory infections and all-cause mortality. Evidence for cardiovascular effects is mixed, but a few recent studies have reported associations for specific cardiovascular end points. Insufficient research exists to identify specific population subgroups that are more susceptible to wildfire smoke exposure. *Conclusions:* Consistent evidence from a large number of studies indicates that wildfire smoke exposure is associated with respiratory morbidity with growing evidence supporting an association with all-cause mortality. More research is needed to clarify which causes of mortality may be associated with wildfire smoke, whether cardiovascular outcomes are associated with wildfire smoke, and if certain populations are more susceptible.

Wildfire-specific fine particulate matter and risk of hospital admissions in urban and rural counties. Liu JC, Wilson A, Mickley LJ, Dominici F, Ebisu K, et al. (2017). *Epidemiology*, 28(1): 77-85. <http://dx.doi.org/10.1097/EDE.0000000000000556>

Geographic Location: Western United States
Type of Reference: Research Paper

Abstract: *Background:* The health impacts of wildfire smoke, including fine particles (PM_{2.5}), are not well understood and may differ from those of PM_{2.5} from other sources due to differences in concentrations and chemical composition. *Methods:* First, for the entire Western United States (561 counties) for 2004-2009, we estimated daily PM_{2.5} concentrations directly attributable to wildfires (wildfires-specific PM_{2.5}), using a global chemical transport model. Second, we defined smoke wave as ≥ 2 consecutive days with daily wildfire-specific PM_{2.5} > 20 micrograms per meter ($\mu\text{g}/\text{m}$), with sensitivity analysis considering 23, 28, and 37 $\mu\text{g}/\text{m}$. Third, we estimated the risk of cardiovascular and respiratory hospital admissions associated with smoke waves for Medicare enrollees. We used a generalized linear mixed model to estimate the relative risk of hospital admissions on smoke wave days compared with matched comparison days without wildfire smoke. *Results:* We estimated that about 46 million people of all ages were exposed to at least one smoke wave during 2004 to 2009 in the Western United States. Of these, 5 million are Medicare enrollees (≥ 65 years). We found a 7.2% (95% confidence interval: 0.25%, 15%) increase in risk of respiratory admissions during smoke wave days with high wildfire-specific PM_{2.5} ($> 37 \mu\text{g}/\text{m}$) compared with matched non smoke wave days. We did not observe an association between smoke wave days with wildfire-specific PM_{2.5} $\leq 37 \mu\text{g}/\text{m}$ and respiratory or cardiovascular admissions. Respiratory effects of wildfire-specific PM_{2.5} may be stronger than that of PM_{2.5} from



other sources. *Conclusion:* Short-term exposure to wildfire-specific PM_{2.5} was associated with risk of respiratory diseases in the elderly population in the Western United States during severe smoke days.

Vector-borne and infectious diseases

Warming temperatures and changes in precipitation can affect vector-borne pathogen transmission and disease patterns. These changes can influence seasonality, distribution and prevalence of vector-borne diseases. In California, West Nile Virus poses the greatest mosquito-borne disease threat. In addition to mosquito vectors, climate change will invariably impact the prevalence of tick-borne diseases, such as Lyme Disease.

Recent and projected future climatic suitability of North America for the Asian tiger mosquito *Aedes albopictus*. Ogden NH, Milka R, Caminade C, and Gachon P (2014). *Parasites and Vectors*, 7:532. <http://dx.doi.org/10.1186/s13071-014-0532-4>

Geographic Location: North America

Type of Reference: Research Paper

Abstract: *Background:* Since the 1980s, populations of the Asian tiger mosquito *Aedes albopictus* have become established in south-eastern, eastern and central United States, extending to approximately 40°N. *Ae. albopictus* is a vector of a wide range of human pathogens including dengue and chikungunya viruses, which are currently emerging in the Caribbean and Central America and posing a threat to North America. *Methods:* The risk of *Ae. albopictus* expanding its geographic range in North America under current and future climate was assessed using three climatic indicators of *Ae. albopictus* survival: overwintering conditions (OW), OW combined with annual air temperature (OWAT), and a linear index of precipitation and air temperature suitability expressed through a sigmoidal function (SIG). The capacity of these indicators to predict *Ae. albopictus* occurrence was evaluated using surveillance data from the United States. Projected future climatic suitability for *Ae. albopictus* was obtained using output of nine Regional Climate Model experiments (RCMs). *Results:* OW and OWAT showed >90% specificity and sensitivity in predicting observed *Ae. albopictus* occurrence and also predicted moderate to high risk of *Ae. albopictus* invasion in Pacific coastal areas of the United States and Canada under current climate. SIG also well predicted observed *Ae. albopictus* occurrence (ROC area under the curve was 0.92) but predicted wider current climatic suitability in the north-central and north-eastern United States and south-eastern Canada. RCM output projected modest (circa 500 km) future northward range expansion of *Ae. albopictus* by the 2050s when using OW and OWAT indicators, but greater (600–1000 km) range expansion, particularly in eastern and central Canada, when using the SIG indicator. Variation in future possible distributions of *Ae. albopictus* was greater amongst the climatic indicators used than



amongst the RCM experiments. *Conclusions:* Current *Ae. albopictus* distributions were well predicted by simple climatic indicators and northward range expansion was predicted for the future with climate change. However, current and future predicted geographic distributions of *Ae. albopictus* varied amongst the climatic indicators used. Further field studies are needed to assess which climatic indicator is the most accurate in predicting regions suitable for *Ae. albopictus* survival in North America.

The global distribution of the arbovirus vectors *Aedes aegypti* and *Ae. albopictus*.
Kraemar MUG, Sinka ME, Duda KA, Mylne AQN, Shearer FM, et al. (2015). *eLife*, 4: e08347. <https://dx.doi.org/10.7554/eLife.08347.001>.

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Dengue and chikungunya are increasing global public health concerns due to their rapid geographical spread and increasing disease burden. Knowledge of the contemporary distribution of their shared vectors, *Aedes aegypti* and *Aedes albopictus* remains incomplete and is complicated by an ongoing range expansion fueled by increased global trade and travel. Mapping the global distribution of these vectors and the geographical determinants of their ranges is essential for public health planning. Here we compile the largest contemporary database for both species and pair it with relevant environmental variables predicting their global distribution. We show *Aedes* distributions to be the widest ever recorded; now extensive in all continents, including North America and Europe. These maps will help define the spatial limits of current autochthonous transmission of dengue and chikungunya viruses. It is only with this kind of rigorous entomological baseline that we can hope to project future health impacts of these viruses.



Toward a mechanistic understanding of environmentally forced zoonotic disease emergence: Sin nombre hantavirus. Carver S, Mills JN, Parmenter CA, Parmenter RR, Richardson KS, et al. (2015). *Bioscience*, **65**(7): 651-666. <http://dx.doi.org/10.1093/biosci/biv047>

Geographic Location: United States

Type of Reference: Review Article (with new analyses based on published data from literature)

Description: Understanding the environmental drivers of zoonotic reservoir and human interactions is crucial to understanding disease risk, but these drivers are poorly predicted. We propose a mechanistic understanding of human–reservoir interactions, using hantavirus pulmonary syndrome as a case study. Crucial processes underpinning the disease’s incidence remain poorly studied, including the connectivity among natural and peridomestic deer mouse host activity, virus transmission, and human exposure. We found that disease cases were greatest in arid states and declined exponentially with increasing precipitation. Within arid environments, relatively rare climatic conditions (e.g., El Niño) are associated with increased rainfall and reservoir abundance, producing more frequent virus transmission and host dispersal. We suggest that deer mice increase their occupancy of peridomestic structures during spring–summer, amplifying intraspecific transmission and human infection risk. Disease incidence in arid states may increase with predicted climatic changes. Mechanistic approaches incorporating reservoir behavior, reservoir–human interactions, and pathogen spillover could enhance our understanding of global hantavirus ecology, with applications to other directly transmitted zoonoses.

Meteorological conditions associated with increased incidence of West Nile Virus disease in the United States, 2004–2012. Hahn MB, Monaghan AJ, Hayden MH, Eisen RJ, Delorey MJ, et al. (2015). *American Journal of Tropical Medicine and Hygiene*, **92**(5): 1013–1022. <http://dx.doi.org/10.4269/ajtmh.14-0737>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: West Nile virus (WNV) is a leading cause of mosquito-borne disease in the United States. Annual seasonal outbreaks vary in size and location. Predicting where and when higher than normal WNV transmission will occur can help direct limited public health resources. We developed models for the contiguous United States to identify meteorological anomalies associated with above average incidence of WNV neuroinvasive disease from 2004 to 2012. We used county-level WNV data reported to ArboNET and meteorological data from the North American Land Data Assimilation System. As a result of geographic differences in WNV transmission, we divided the United States into East and West, and 10 climate regions. Above average annual temperature was associated with increased likelihood of higher than normal WNV disease incidence, nationally and in most regions. Lower than average annual total



precipitation was associated with higher disease incidence in the eastern United States, but the opposite was true in most western regions. Although multiple factors influence WNV transmission, these findings show that anomalies in temperature and precipitation are associated with above average WNV disease incidence. Readily accessible meteorological data may be used to develop predictive models to forecast geographic areas with elevated WNV disease risk before the coming season.

Impact of climate change on human infectious diseases: Empirical evidence and human adaptation. Wu X, Lu Y, Zhou S, Chen L, and Xu B (2016). *Environmental International*, **86**: 14-23. <http://dx.doi.org/10.1016/j.envint.2015.09.007>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Climate change refers to long-term shifts in weather conditions and patterns of extreme weather events. It may lead to changes in health threat to human beings, multiplying existing health problems. This review examines the scientific evidences on the impact of climate change on human infectious diseases. It identifies research progress and gaps on how human society may respond to, adapt to, and prepare for the related changes. Based on a survey of related publications between 1990 and 2015, the terms used for literature selection reflect three aspects — the components of infectious diseases, climate variables, and selected infectious diseases. Humans' vulnerability to the potential health impacts by climate change is evident in literature. As an active agent, human beings may control the related health effects that may be effectively controlled through adopting proactive measures, including better understanding of the climate change patterns and of the compound disease-specific health effects, and effective allocation of technologies and resources to promote healthy lifestyles and public awareness. The following adaptation measures are recommended: 1) to go beyond empirical observations of the association between climate change and infectious diseases and develop more scientific explanations, 2) to improve the prediction of spatial-temporal process of climate change and the associated shifts in infectious diseases at various spatial and temporal scales, and 3) to establish locally effective early warning systems for the health effects of predicated climate change.

Impact of El Niño Southern Oscillation on infectious disease hospitalization risk in the United States. Fisman DN, Tuite AR and Brown KA (2016). *Proceedings of the National Academy of Sciences USA*, **113**(51): 14589-14594. <http://dx.doi.org/10.1073/pnas.1604980113>

Geographic Location: United States

Type of Reference: Research Paper



Description: Although the global climate is changing at an unprecedented rate, links between weather and infectious disease have received little attention in high income countries. The "El Niño Southern Oscillation" (ENSO) occurs irregularly and is associated with changing temperature and precipitation patterns. We studied the impact of ENSO on infectious diseases in four census regions in the United States. We evaluated infectious diseases requiring hospitalization using the US National Hospital Discharge Survey (1970-2010) and five disease groupings that may undergo epidemiological shifts with changing climate: (i) vector-borne diseases, (ii) pneumonia and influenza, (iii) enteric disease, (iv) zoonotic bacterial disease, and (v) fungal disease. ENSO exposure was based on the Multivariate ENSO Index. Distributed lag models, with adjustment for seasonal oscillation and long-term trends, were used to evaluate the impact of ENSO on disease incidence over lags of up to 12 months. ENSO was associated more with vector-borne disease [relative risk (RR) 2.96, 95% confidence interval (CI) 1.03-8.48] and less with enteric disease (0.73, 95% CI 0.62-0.87) in the Western region; the increase in vector-borne disease was attributable to increased risk of rickettsioses and tick-borne infectious diseases. By contrast, ENSO was associated with more enteric disease in non-Western regions (RR 1.12, 95% CI 1.02-1.15). The periodic nature of ENSO may make it a useful natural experiment for evaluation of the impact of climatic shifts on infectious disease risk. The impact of ENSO suggests that warmer temperatures and extreme variation in precipitation events influence risks of vector-borne and enteric disease in the United States.

Anthropogenic impacts on mosquito populations in North America over the past century. Rochlin I, Faraji A, Ninivaggi DV, Barker CM, and Kilpatrick AM (2016). *Nature Communications*, 7: 13604. <http://dx.doi.org/10.1038/ncomms13604>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: The effect of global climate change on infectious disease remains hotly debated because multiple extrinsic and intrinsic drivers interact to influence transmission dynamics in nonlinear ways. The dominant drivers of widespread pathogens, like West Nile virus, can be challenging to identify due to regional variability in vector and host ecology, with past studies producing disparate findings. Here, we used analyses at national and state scales to examine a suite of climatic and intrinsic drivers of continental-scale West Nile virus epidemics, including an empirically derived mechanistic relationship between temperature and transmission potential that accounts for spatial variability in vectors. We found that drought was the primary climatic driver of increased West Nile virus epidemics, rather than within-season or winter temperatures, or precipitation independently. Local-scale data from one region suggested drought increased epidemics via changes in mosquito infection prevalence rather than mosquito abundance. In addition, human acquired immunity following regional epidemics limited subsequent transmission in many states. We show that over the next 30 years, increased drought severity from climate change could triple West Nile virus cases, but



only in regions with low human immunity. These results illustrate how changes in drought severity can alter the transmission dynamics of vector-borne diseases.

Effects of climate and climate change on vectors and vector-borne diseases: ticks are different. Ogden NH and Lindsay LR (2016). *Trends in Parasitology*, **32**: 646-56. <http://dx.doi.org/10.1016/j.pt.2016.04.015>

Geographic Location: Global

Type of Reference: Review Article

Abstract: There has been considerable debate as to whether global risk from vector-borne diseases will be impacted by climate change. This has focused on important mosquito-borne diseases that are transmitted by the vectors from infected to uninfected humans. However, this debate has mostly ignored the biological diversity of vectors and vector-borne diseases. Here, we review how climate and climate change may impact those most divergent of arthropod disease vector groups: multivoltine insects and hard-bodied (ixodid) ticks. We contrast features of the life cycles and behaviour of these arthropods, and how weather, climate, and climate change may have very different impacts on the spatiotemporal occurrence and abundance of vectors, and the pathogens they transmit.

West Nile virus, climate change, and circumpolar vulnerability. Hoover KC and Barker CM (2016). *Wiley Interdisciplinary Reviews: Climate Change*, **7**(2): 283-300. <http://dx.doi.org/10.1002/wcc.382>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Climate has strong impacts on the spatial ranges of vector-borne infectious diseases as well as the timing and intensity of disease outbreaks; these and shifting challenges to human health driven by future climate change are critical concerns. Many diseases of tropical origin, including West Nile virus (WNV), are sensitive to climate and likely to change their distributions in the coming decades. The 1999 outbreak of WNV in North America is an example of rapid viral adaptation to a new geographic area while recent outbreaks in Europe demonstrate the capacity of multiple viral strains to expand rapidly. WNV is one of the most widely distributed arboviruses and has displayed high rates of mutability, adaptability, and virulence. Northward expansion of WNV is happening in Europe and North America and may make WNV an increasingly worrying health risk at higher latitudes. Circumpolar northward expansion of WNV's enzootic range appears unlikely over the coming century—at least for sustained enzootic transmission—but isolated and ephemeral transmission events might occur if the virus were to be introduced by migrating birds during warm months. Human populations in this area are at greater risk for health impacts from WNV transmission due to limited



healthcare in rural areas, higher underlying morbidity in indigenous populations, and prolonged human-environment interactions (in populations engaging in traditional lifestyles). This review presents a multidisciplinary synthesis on WNV and climate change, potential for WNV expansion, and the vulnerability of the circumpolar north. For further resources related to this article, please visit the WIREs website.

Drought and immunity determine the intensity of West Nile virus epidemics and climate change impacts. Paull SH, Horton DE, Ashfaq M, Rastogi D, Kramer LD, et al. (2017). *Proceedings of the Royal Society B*, **284**: 2016-2078. <http://dx.doi.org/10.1098/rspb.2016.2078>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: The effect of global climate change on infectious disease remains hotly debated because multiple extrinsic and intrinsic drivers interact to influence transmission dynamics in nonlinear ways. The dominant drivers of widespread pathogens, like West Nile virus, can be challenging to identify due to regional variability in vector and host ecology, with past studies producing disparate findings. Here, we used analyses at national and state scales to examine a suite of climatic and intrinsic drivers of continental-scale West Nile virus epidemics, including an empirically derived mechanistic relationship between temperature and transmission potential that accounts for spatial variability in vectors. We found that drought was the primary climatic driver of increased West Nile virus epidemics, rather than within-season or winter temperatures, or precipitation independently. Local-scale data from one region suggested drought increased epidemics via changes in mosquito infection prevalence rather than mosquito abundance. In addition, human acquired immunity following regional epidemics limited subsequent transmission in many states. We show that over the next 30 years, increased drought severity from climate change could triple West Nile virus cases, but only in regions with low human immunity. These results illustrate how changes in drought severity can alter the transmission dynamics of vector-borne diseases.

Tick-borne zoonoses in the United States: persistent and emerging threats to human health. Eisen RJ, Kugeler KJ, Eisen L, Beard CB, and Paddock CD (2017). *ILAR*, **58**(3): 1-17. <https://dx.doi.org/10.1093/ilar/ilx005>

Geographic Location: United States

Type of Reference: Review Article

Abstract: In the United States, ticks transmit the greatest diversity of arthropod-borne pathogens and are responsible for the most cases of all vector-borne diseases. In recent decades, the number of reported cases of notifiable tick-borne diseases has steadily increased, geographic distributions of many ticks and tick-borne diseases have



expanded, and new tick-borne disease agents have been recognized. In this review, we (1) describe the known disease agents associated with the most commonly human-biting ixodid ticks, (2) review the natural histories of these ticks and their associated pathogens, (3) highlight spatial and temporal changes in vector tick distributions and tick-borne disease occurrence in recent decades, and (4) identify knowledge gaps and barriers to more effective prevention of tick-borne diseases. We describe 12 major tick-borne diseases caused by 15 distinct disease agents that are transmitted by the 8 most commonly human-biting ixodid ticks in the United States. Notably, 40% of these pathogens were described within the last two decades. Our assessment highlights the importance of animal studies to elucidate how tick-borne pathogens are maintained in nature, as well as advances in molecular detection of pathogens which has led to the discovery of several new tick-borne disease agents.

Impacts on animals

Animals reproduce and survive within specific habitat ranges defined by climatic and environmental conditions. Scientific evidence suggests that terrestrial, marine and freshwater organisms worldwide are impacted by recent warming, and have exhibited certain responses, including: shifting range boundaries; changes in the timing of growth stages; changes in body size and other morphological features; and changes in population abundance. While some species are expected to adapt to new climate conditions, not all may have the ability to respond to changes in climate.

Impacts of ocean acidification on marine organisms

As the ocean absorbs CO₂ released into the atmosphere (see “Drivers, Ocean acidification,” above) the chemistry of seawater changes, a process known as ocean acidification. Several biological processes in marine organisms are known to be sensitive to ocean acidification. The best-documented and most widely observed biological effects are decreased calcification rates and/or shell dissolution in a wide range of shell-forming organisms, including plankton, mollusks, and corals.

Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. Kroeker KJ, Kordas RL, Crim R, Hendriks IE, Ramajo L, et al. (2013). *Global Change Biology*, **19**: 1884-1896.
<http://dx.doi.org/10.1111/gcb.12179>

Geographic Location: Global

Type of Reference: Research Paper (Meta-Analysis)

Abstract: Ocean acidification represents a threat to marine species worldwide, and forecasting the ecological impacts of acidification is a high priority for science, management, and policy. As research on the topic expands at an exponential rate, a



comprehensive understanding of the variability in organisms' responses and corresponding levels of certainty is necessary to forecast the ecological effects. Here, we perform the most comprehensive meta-analysis to date by synthesizing the results of 228 studies examining biological responses to ocean acidification. The results reveal decreased survival, calcification, growth, development and abundance in response to acidification when the broad range of marine organisms is pooled together. However, the magnitude of these responses varies among taxonomic groups, suggesting there is some predictable trait-based variation in sensitivity, despite the investigation of approximately 100 new species in recent research. The results also reveal an enhanced sensitivity of mollusk larvae, but suggest that an enhanced sensitivity of early life history stages is not universal across all taxonomic groups. In addition, the variability in species' responses is enhanced when they are exposed to acidification in multi-species assemblages, suggesting that it is important to consider indirect effects and exercise caution when forecasting abundance patterns from single-species laboratory experiments. Furthermore, the results suggest that other factors, such as nutritional status or source population, could cause substantial variation in organisms' responses. Last, the results highlight a trend towards enhanced sensitivity to acidification when taxa are concurrently exposed to elevated seawater temperature.

***Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem.** Bednaršek N, Feely RA, Reum JCP, Peterson B, Menkel J, et al. (2014). *Proceedings of the Royal Society B*, **281**: 20140123. <http://dx.doi.org/10.1098/rspb.2014.0123>

Geographic Location: Pacific Coast, including California

Type of Reference: Research Paper

Abstract: Few studies to date have demonstrated widespread biological impacts of ocean acidification (OA) under conditions currently found in the natural environment. From a combined survey of physical and chemical water properties and biological sampling along the Washington–Oregon–California coast in August 2011, we show that large portions of the shelf waters are corrosive to pteropods in the natural environment. We show a strong positive correlation between the proportion of pteropod individuals with severe shell dissolution damage and the percentage of undersaturated water in the top 100 meters with respect to aragonite. We found 53% of onshore individuals and 24% of offshore individuals on average to have severe dissolution damage. Relative to pre-industrial CO₂ concentrations, the extent of undersaturated waters in the top 100 meters of the water column has increased over sixfold along the California Current Ecosystem (CCE). We estimate that the incidence of severe pteropod shell dissolution owing to anthropogenic OA has doubled in near shore habitats since pre-industrial conditions across this region and is on track to triple by 2050. These results



demonstrate that habitat suitability for pteropods in the coastal CCE is declining. The observed impacts represent a baseline for future observations towards understanding broader scale OA effects.

Predicting the effects of ocean acidification on predator-prey interactions: A conceptual framework based on coastal molluscs. Kroeker KJ, Sanford E, Jellison BM, and Gaylord B (2014). *Biological Bulletin*, **226**: 221-222. <http://dx.doi.org/10.1086/BBLv226n3p211>

Geographic Location: Global

Type of Reference: Review Article

Abstract: The influence of environmental change on species interactions will affect population dynamics and community structure in the future, but our current understanding of the outcomes of species interactions in a high-CO₂ world is limited. Here, we draw upon emerging experimental research examining the effects of ocean acidification on coastal molluscs to provide hypotheses of the potential impacts of high-CO₂ on predator-prey interactions. Coastal molluscs, such as oysters, mussels, and snails, allocate energy among defenses, growth, and reproduction. Ocean acidification increases the energetic costs of physiological processes such as acid-base regulation and calcification. Impacted molluscs can display complex and divergent patterns of energy allocation to defenses and growth that may influence predator-prey interactions; these include changes in shell properties, body size, tissue mass, immune function, or reproductive output. Ocean acidification has also been shown to induce complex changes in chemoreception, behavior, and inducible defenses, including altered cue detection and predator avoidance behaviors. Each of these responses may ultimately alter the susceptibility of coastal molluscs to predation through effects on predator handling time, satiation, and search time. While many of these effects may manifest as increases in *per capita* predation rates on coastal molluscs, the ultimate outcome of predator-prey interactions will also depend on how ocean acidification affects the specified predators, which also exhibit complex responses to ocean acidification. Changes in predator-prey interactions could have profound and unexplored consequences for the population dynamics of coastal molluscs in a high-CO₂ ocean.

Nighttime dissolution in a temperate coastal ocean ecosystem increases under acidification. Kwiatkowski L, Gaylord B, Hill TM, Hosfelt J, Kroeker KJ, et al. (2016). *Scientific Reports*, **6**: 22984. <http://dx.doi.org/10.1038%2Fsrep22984>

Geographic Location: Bodega Marine Reserve, California

Type of Reference: Research Paper

Abstract: Anthropogenic emissions of carbon dioxide (CO₂) are causing ocean acidification, lowering seawater aragonite (CaCO₃) saturation state (Ω_{arag}), with



potentially substantial impacts on marine ecosystems over the 21st Century. Calcifying organisms have exhibited reduced calcification under lower saturation state conditions in aquaria. However, the in situ sensitivity of calcifying ecosystems to future ocean acidification remains unknown. Here we assess the community level sensitivity of calcification to local CO₂-induced acidification caused by natural respiration in an unperturbed, biodiverse, temperate intertidal ecosystem. We find that on hourly timescales nighttime community calcification is strongly influenced by Ω_{arag} , with greater net calcium carbonate dissolution under more acidic conditions. Daytime calcification however, is not detectably affected by Ω_{arag} . If the short-term sensitivity of community calcification to Ω_{arag} is representative of the long-term sensitivity to ocean acidification, nighttime dissolution in these intertidal ecosystems could more than double by 2050, with significant ecological and economic consequences.

Estimates of the direct effect of seawater pH on the survival rate of species groups in the California Current Ecosystem. Busch DS and McElhany P (2016). *PLoS ONE*, 11(8): e0160669. <http://dx.doi.org/10.1371/journal.pone.0160669>

Geographic Location: Global, including California Current, Pacific Ocean
Type of Reference: Review Article

Abstract: Ocean acidification (OA) has the potential to restructure ecosystems due to variation in species sensitivity to the projected changes in ocean carbon chemistry. Ecological models can be forced with scenarios of OA to help scientists, managers, and other stakeholders understand how ecosystems might change. We present a novel methodology for developing estimates of species sensitivity to OA that are regionally specific, and applied the method to the California Current ecosystem. To do so, we built a database of all published literature on the sensitivity of temperate species to decreased pH. This database contains 393 papers on 285 species and 89 multi-species groups from temperate waters around the world. Research on urchins and oysters and on adult life stages dominates the literature. Almost a third of the temperate species studied to date occur in the California Current. However, most laboratory experiments use control pH conditions that are too high to represent average current chemistry conditions in the portion of the California Current water column where the majority of the species live. We developed estimates of sensitivity to OA for functional groups in the ecosystem, which can represent single species or taxonomically diverse groups of hundreds of species. We based these estimates on the amount of available evidence derived from published studies on species sensitivity, how well this evidence could inform species sensitivity in the California Current ecosystem, and the agreement of the available evidence for a species/species group. This approach is similar to that taken by the Intergovernmental Panel on Climate Change to characterize certainty when summarizing scientific findings. Most functional groups (26 of 34) responded negatively to OA conditions, but when uncertainty in sensitivity was considered, only 11 groups



had relationships that were consistently negative. Thus, incorporating certainty about the sensitivity of species and functional groups to OA is an important part of developing robust scenarios for ecosystem projections.

The influence of Pacific Equatorial Water on fish diversity in the southern California Current System. McClatchie S, Thompson AR, Alin SR, Siedlecki S, Watson W, and Bograd SJ (2016). *Journal of Geophysical Research Oceans*, 121: 6121–6136. <http://dx.doi.org/10.1002/2016JC011672>

Geographic Location: California Current System, Pacific Ocean

Type of Reference: Research Paper

Description: The California Undercurrent transports Pacific Equatorial Water (PEW) into the Southern California Bight from the eastern tropical Pacific Ocean. PEW is characterized by higher temperatures and salinities, with lower pH, representing a source of potentially corrosive (aragonite, $\Omega < 1$) water to the region. We use ichthyoplankton assemblages near the cores of the California Current and the California Undercurrent to determine whether PEW influenced fish diversity. We use hydrographic data to characterize the interannual and seasonal variability of estimated pH and aragonite saturation with depth. Although there is substantial variability in PEW presence as measured by spice on the 26.25–26.75 isopycnal layer, as well as in pH and aragonite saturation, we found fish diversity to be stable over the decades 1985–1996 and 1999–2011. We detected significant difference in species structure during the 1998 La Niña period, due to reduced species evenness. Species richness due to rare species was higher during the 1997/1998 El Niño compared to the La Niña but the effect on species structure was undetectable. Lack of difference in the species abundance structure in the decade before and after the 1997/1999 ENSO event showed that the assemblage reverted to its former structure following the ENSO perturbation, indicating resilience. While the interdecadal species structure remained stable, the long tail of the distributions shows that species richness increased between the decades consistent with intrusion of warm water with more diverse assemblages into the southern California region.

New ocean, new needs: Application of pteropod dissolution as a biological indicator for marine resource management. Bednaršek N, Klinger T, Harvey CJ, Weisberg S, McCabe RM, et al. (2017). *Ecological Indicators*, **76**: 240–244. <http://dx.doi.org/10.1016/j.ecolind.2017.01.025>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Pteropods, planktonic marine snails with a cosmopolitan distribution, are highly sensitive to changing ocean chemistry. Graphical abstract shows pteropod



responses to be related to aragonite saturation state, with progressing decrease in Ω_{ar} causing deteriorating biological conditions. Under high saturation state ($\Omega_{ar} > 1.1$; zone 0), pteropods are healthy with no presence of stress or shell dissolution. With decreasing Ω_{ar} (zone 1), pteropod stress is demonstrated through increased dissolution and reduced calcification. At $\Omega_{ar} < 0.8$ (zones 2 and 3), severe dissolution and absence of calcification prevail; the impairment is followed by significant damages. Pteropods responses to ocean acidification (OA) are closely correlated to shell dissolution that is characterized by clearly delineated thresholds. Yet the practical utility of these species as indicators of the status of marine ecosystem integrity has been overlooked. Here, we set out the scientific and policy rationales for the use of pteropods as a biological indicator appropriate for low-cost assessment of the effect of anthropogenic OA on marine ecosystems. While no single species or group of species can adequately capture all aspects of ecosystem change, pteropods are sensitive, specific, quantifiable indicators of OA's effects on marine biota. In an indicator screening methodology, shell dissolution scored highly compared to other indicators of marine ecological integrity. As the socio-economic challenges of changing ocean chemistry continue to grow in coming decades, the availability of such straightforward and sensitive metrics of impact will become indispensable. Pteropods can be a valuable addition to suites of indicators intended to support OA water quality assessment, ecosystem-based management, policy development, and regulatory applications.

Range shifts

Climate conditions typically constrain a species' geographic range. Some animals respond to changing conditions by systematically moving to geographic areas where the conditions are closer to their physiologic temperature and moisture tolerances. These species are said to be tracking their climatic niche. The area occupied by a species might increase, decrease or remain constant, depending upon gains or losses in areas with suitable climate conditions. Certain topographical or geological features, as well as habitat alteration by humans, may prevent movement to new areas.

Changes in the geographical distribution of species have been observed across a wide range of taxonomic groups and geographical locations. Movement towards higher latitudes or higher elevations are most commonly observed.

Ecological and life-history traits explain recent boundary shifts in elevation and latitude of western North American songbirds.

Auer SK and King DI (2014). *Global Ecology and Biogeography*, 23(8): 867-875. <http://dx.doi.org/10.1111/geb.12174>

Geographic Location: North America

Type of Reference: Research Paper

Abstract: *Aim:* Species are expected to move uphill or poleward in response to climate change, yet their distributions show idiosyncratic responses; many species are moving



in the predicted direction, but others are not shifting at all or are shifting downhill or towards the equator. Fundamental questions remain about the causes of interspecific variation in range responses and whether shifts along elevational and latitudinal gradients are correlated. We examined whether shifts in northern-latitude and upper-elevation boundaries of western North American songbirds over a 35-year period were correlated and whether species ecological and life-history traits explained interspecific variation in observed shifts. *Location:* North America. *Methods:* We used data from the North American Breeding Bird Survey to determine shifts in northern-latitude and upper-elevation boundaries of 40 North American songbird species between two time periods, 1977–81 and 2006–11. We used an analysis of covariance approach that controlled for species population trends and changes in survey effort to test whether: (1) songbirds shifted in elevation, latitude or both; (2) shifts in elevation and latitude were correlated; and (3) responses could be explained by species-level traits including life history, ecological generalization and dispersal capability. *Results:* The majority of species shifted uphill and poleward during this period, but there was no correlation between the distances that species range boundaries shifted in elevation and latitude. Species with smaller clutch sizes and narrower diet breadths exhibited greater northward shifts, while species with larger clutch sizes and narrower diet breadths exhibited greater uphill shifts. *Main conclusions:* Shifts in latitude and elevation were not correlated. However, a common set of species-level traits explained differential responses among species to climate change. Consideration of shifts in both elevation and latitude is needed to understand the full extent to which species are tracking changing climates.

Climate change impacts on bumblebees converge across continents. Kerr JT, Pindar A, Galpern P, Packer L, Potts SG, Roberts SM, et al. (2015). *Science*, 349(6244): 177-180. <http://dx.doi.org/10.1126/science.aaa7031>

Geographic Location: Europe and North America
Type of Reference: Review Article

Abstract: For many species, geographical ranges are expanding toward the poles in response to climate change, while remaining stable along range edges nearest the equator. Using long-term observations across Europe and North America over 110 years, we tested for climate change–related range shifts in bumblebee species across the full extents of their latitudinal and thermal limits and movements along elevation gradients. We found cross-continently consistent trends in failures to track warming through time at species’ northern range limits, range losses from southern range limits, and shifts to higher elevations among southern species. These effects are independent of changing land uses or pesticide applications and underscore the need to test for climate impacts at both leading and trailing latitudinal and thermal limits for species.



Endangered Quino checkerspot butterfly and climate change: Short-term success but long-term variability? Parmesan C, Williams-Anderson A, Moskwik M, Mikheyev AS, and Singer MC (2015). *Journal of Insect Conservation*, **19**(2): 185-204. <http://dx.doi.org/10.1007/s10841-014-9743-4>

Geographic Location: North America

Type of Reference: Research Paper

Abstract: The butterfly *Euphydryas editha* is known to be vulnerable to climate events that exacerbate natural phenological asynchrony between insect and hosts. In prior work, populations of *E. editha* have been more persistent at high latitudes and high elevations than in the south and at low elevations, consistent with response to observed warming climate. However, poleward range shifts by the endangered subspecies *E. e. equino* are blocked by urbanization and range shifts to higher elevation may require host shifts. Prior studies were inconclusive as to whether elevational and host shifts were already occurring. Here, we re-evaluate this scenario with new evidence from molecular genetics, host-choice behaviour and field recording of butterfly distribution. We found a statistically significant upward shift in population distribution since 2009. Insects in the expanding region were neither genomic outliers within Quino nor specifically adapted to their principal local host genus, *Collinsia*. These diverse data collectively support the hypothesis that an elevational range expansion is already in progress, accompanied and facilitated by a shift of principal host from *Plantago* to *Collinsia*. Quino appears resilient to warming climate. However, projections indicate that most or all of Quino's current range in the USA, including the new high elevation expansion, will become uninhabitable. Our most frequent projected future range (circa 2050) is circa 400 kilometers northward from current populations, hence conservation of Quino may eventually require assisted colonization. For now, Critical Habitat (sensu Endangered Species Act) has been designated at sites around the new upper elevational limit that were not known to be occupied. Designating Critical Habitat outside the historic range is a pioneering response to climate change. This politically challenging, non-traditional, climate change-oriented conservation effort exemplifies flexible thinking needed for species vulnerable to climate change.

Warm oceanographic anomalies and fishing pressure drive seabird nesting north. Velarde E, Ezcurra E, Horn MH, and Patton RT (2015). *Science Advances*, **1**(5): e1400210. <http://dx.doi.org/10.1126%2Fsciadv.1400210>

Geographic Location: Mexico and Southern California

Type of Reference: Research Paper

Abstract: Parallel studies of nesting colonies in Mexico and the United States show that Elegant Terns (*Thalasseus elegans*) have expanded from the Gulf of California Midriff Island Region into Southern California, but the expansion fluctuates from year to year. A strong inverse relationship between nesting pairs in three Southern California nesting areas [San Diego saltworks, Bolsa Chica Ecological Reserve, and Los Angeles Harbor



(1991 to 2014)] and Isla Rasa in the Midriff (1980 to 2014) shows that terns migrate northward when confronting warm oceanographic anomalies ($>1.0^{\circ}\text{Celsius}$), which may decrease fish availability and hamper nesting success. Migration pulses are triggered by sea surface temperature anomalies localized in the Midriff and, secondarily, by reductions in the sardine population as a result of intensive fishing. This behavior is new; before year 2000, the terns stayed in the Midriff even when oceanographic conditions were adverse. Our results show that terns are responding dynamically to rapidly changing oceanographic conditions and fish availability by migrating 600 kilometers northwest in search of more productive waters.

The pace of past climate change vs. potential bird distributions and land use in the United States. Bateman BL, Pidgeon AM, Radeloff VC, Anderwal J, Thogmartin WE, et al. (2016). *Global Change Biology*, **22**: 1130-1144.
<http://dx.doi.org/10.1111/gcb.13154>

Geographic Location: United States

Type of Reference: Research Paper

Abstract: Climate change may drastically alter patterns of species distributions and richness, but predicting future species patterns in occurrence is challenging. Significant shifts in distributions have already been observed, and understanding these recent changes can improve our understanding of potential future changes. We assessed how past climate change affected potential breeding distributions for landbird species in the conterminous United States. We quantified the bioclimatic velocity of potential breeding distributions, that is, the pace and direction of change for each species' suitable climate space over the past 60 years. We found that potential breeding distributions for landbirds have shifted substantially with an average velocity of 1.27 km yr^{-1} , about double the pace of prior distribution shift estimates across terrestrial systems globally (0.61 km yr^{-1}). The direction of shifts was not uniform. The majority of species' distributions shifted west, northwest, and north. Multidirectional shifts suggest that changes in climate conditions beyond mean temperature were influencing distributional changes. Indeed, precipitation variables that were proxies for extreme conditions were important variables across all models. There were winners and losers in terms of the area of distributions; many species experienced contractions along west and east distribution edges, and expansions along northern distribution edges. Changes were also reflected in the potential species richness, with some regions potentially gaining species (Midwest, East) and other areas potentially losing species (Southwest). However, the degree to which changes in potential breeding distributions are manifested in actual species richness depends on landcover. Areas that have become increasingly suitable for breeding birds due to changing climate are often those attractive to humans for agriculture and development. This suggests that many areas



might have supported more breeding bird species had the landscape not been altered. Our study illustrates that climate change is not only a future threat, but something birds are already experiencing.

Population trends influence species ability to track climate change. Ralston J, DeLuca WV, Feldman RE, and King DI (2016). *Global Change Biology*, **23**(4): 1390-1399. <http://dx.doi.org/10.1111/gcb.13478>

Geographic Location: North America

Type of Reference: Research Paper

Abstract: Shifts of distributions have been attributed to species tracking their fundamental climate niches through space. However, several studies have now demonstrated that niche tracking is imperfect, that species' climate niches may vary with population trends, and that geographic distributions may lag behind rapid climate change. These reports of imperfect niche tracking imply shifts in species' realized climate niches. We argue that quantifying climate niche shifts and analyzing them for a suite of species reveal general patterns of niche shifts and the factors affecting species' ability to track climate change. We analyzed changes in realized climate niche between 1984 and 2012 for 46 species of North American birds in relation to population trends in an effort to determine whether species differ in the ability to track climate change and whether differences in niche tracking are related to population trends. We found that increasingly abundant species tended to show greater levels of niche expansion (climate space occupied in 2012 but not in 1980) compared to declining species. Declining species had significantly greater niche unfilling (climate space occupied in 1980 but not in 2012) compared to increasing species due to an inability to colonize new sites beyond their range peripheries after climate had changed at sites of occurrence. Increasing species, conversely, were better able to colonize new sites and therefore showed very little niche unfilling. Our results indicate that species with increasing trends are better able to geographically track climate change compared to declining species, which exhibited lags relative to changes in climate. These findings have important implications for understanding past changes in distribution, as well as modeling dynamic species distributions in the face of climate change.

Nudibranch range shifts associated with the 2014 warm anomaly in the Northeast Pacific. Goddard JHR, Treneman N, Pence WE, et al. (2016). *Bulletin of the Southern California Academy of Sciences*, **115**(1): 15-40. <http://dx.doi.org/10.3160/soca-115-01-15-40.1>

Geographic Location: California and Southern Oregon Coast

Type of Reference: Research Paper



Abstract: The Northeast Pacific Ocean was anomalously warm in 2014, despite ENSO neutral conditions in the tropical Pacific. We document northern range shifts associated with this anomaly for 30 species of nudibranchs and other shallow-water, benthic heterobranch gastropods from southern California to southern Oregon. Nine of these (*Placida cremoniana*, *Trapania velox*, *Doriopsilla fulva*, *Janolus anulatus*, *J. barbarensis*, *Flabellina cooperi*, *Anteaeolidiella chromosoma*, *A. oliviae*, and *Noumeaella rubrofasciata*) were recorded from new northernmost localities, while the remainder were found at or near northern range limits which we show were established mainly during El Niño events. All 30 species have planktotrophic larval development, and six were observed spawning at northern localities, increasing the likelihood that their ranges will continue to shift poleward as the strong 2015-16 El Niño develops. Notable among these was *Okenia rosacea*, usually found south of San Francisco and last observed in Oregon as a single specimen found during the 1997-98 El Niño. In 2015 this bright pink nudibranch reached high densities and was observed spawning throughout northern California and into southern Oregon. *Okenia rosacea* is therefore poised to exploit abundant prey resources previously out of its reach in northern Oregon and Washington. Our results not only demonstrate a striking biological response to the 2014 warm anomaly in the North Pacific Ocean, but also support early physical indications of a larger regional climate shift, one reinforced by long-term global warming. Combined with historical data, these results highlight how shallow-water nudibranchs, with their planktotrophic larvae, short life cycles, conspicuous coloration, and accessibility are excellent biological indicators of ocean climate in the region.

Distribution of a climate-sensitive species at an interior range margin. Ray C, Beever EA, and Rodhouse TJ (2016). *Ecosphere*, 7(6): e01379. <https://dx.doi.org/10.1002/ecs2.1379>

Geographic Location: Northeast California
Type of Reference: Research Paper

Abstract: Advances in understanding the factors that limit a species' range, particularly in the context of climate change, have come disproportionately through investigations at range edges or margins. The margins of a species' range might often correspond with anomalous microclimates that confer habitat suitability where the species would otherwise fail to persist. We addressed this hypothesis using data from an interior, climatic range margin of the American pika (*Ochotona princeps*), an indicator of relatively cool, mesic climates in rocky habitats of western North America. Pikas in Lava Beds National Monument, northeastern California, USA, occur at elevations much lower than predicted by latitude and longitude. We hypothesized that pika occurrence within Lava Beds would be associated primarily with features such as "ice caves" in which sub-surface ice persists outside the winter months. We used data loggers to monitor sub-surface temperatures at cave entrances and at non-cave sites, confirming that temperatures were cooler and more stable at cave entrances. We surveyed habitat characteristics and evidence of pika occupancy across a random sample of cave and non-cave sites over a 2-year period. Pika detection probability was high (~0.97), and the



combined occupancy of cave and non-cave sites varied across the 2 years from 27% to 69%. Contrary to our hypothesis, occupancy was not higher at cave sites. Vegetation metrics were the best predictors of site use by pikas, followed by an edge effect and elevation. The importance of vegetation as a predictor of pika distribution at this interior range margin is congruent with recent studies from other portions of the species' range. However, we caution that vegetation composition depends on microclimate, which might be the proximal driver of pika distribution. The microclimates available in non-cave crevices accessible to small animals have not been characterized adequately for lava landscapes. We advocate innovation in the acquisition and use of microclimatic data for understanding the distributions of many taxa. Appropriately scaled microclimatic data are increasingly available but rarely used in studies of range dynamics.

Apparent climate-mediated loss and fragmentation of core habitat of the American pika in the Northern Sierra Nevada, California, USA. Stewart JAE, Wright DH, and Heckman KA. (2017). *PLoS ONE*, 12(8): e0181834.
<http://dx.doi.org/10.1371/journal.pone.0181834>.

Geographic Location: Northern Sierra Nevada, California
Type of Reference: Research Paper

Abstract: Contemporary climate change has been widely documented as the apparent cause of range contraction at the edge of many species distributions but documentation of climate change as a cause of extirpation and fragmentation of the interior of a species' core habitat has been lacking. Here, we report the extirpation of the American pika (*Ochotona princeps*), a temperature-sensitive small mammal, from a 165-square kilometer (km²) area located within its core habitat in California's Sierra Nevada mountains. While sites surrounding the area still maintain pikas, radiocarbon analyses of pika fecal pellets recovered within this area indicate that former patch occupancy ranges from before 1955, the beginning of the atmospheric spike in radiocarbon associated with above ground atomic bomb testing, to circa 1991. Despite an abundance of suitable rocky habitat climate warming appears to have precipitated their demise. Weather station data reveal a 1.9°Celsius rise in local temperature and a significant decline in snowpack over the period of record, 1910-2015, pushing pika habitat into increasingly tenuous climate conditions during the period of extirpation. This is among the first accounts of an apparently climate-mediated, modern extirpation of a species from an interior portion of its geographic distribution, resulting in habitat fragmentation, and is the largest area yet reported for a modern-era pika extirpation. Our finding provides empirical support to model projections, indicating that even core areas of species habitat are vulnerable to climate change within a timeframe of decades.



The relative influence of change in habitat and climate on elevation range limits in small mammals in Yosemite National Park, California, U.S.A. Santos MJ, Smith AB, Thorne JH, and Moritz C (2017). *Climate change responses*, 4(7): 1-12.
<http://dx.doi.org/10.1111/jbi.12466>

Geographic Location: Yosemite National Park, California

Type of Reference: Research Paper

Abstract: *Background:* Different processes determine species' geographic ranges, including species' responses to changing climate, habitat, or both simultaneously. Here we ask which combination of factors best predicts shifts in the upper and lower elevation range limits and overall range of small mammal species in Yosemite National Park, California, USA across the last 100 years. *Methods:* We used species distribution models (SDMs) to predict elevation range dynamics of small mammals between 1910 and 1930 and 2003 and 2010, based on combinations of habitat and climate variables, and compared the predicted SDM distribution with the "observed" range from occupancy modelling (OM). *Results:* SDM model convergence was successful for eight species. Predictions of elevation range shifts from the SDMs agreed with OM for four of these species; while the other four could be partially predicted. SDMs predicted shifts in lower limits (six correct) better than upper limits (five correct). The five correctly predicted upper limit shifts were best predicted with climate; whereas five out of the six lower elevation shifts included habitat. SDMs were best at predicting range contraction at higher elevations. *Conclusions:* Climate generally had a stronger effect on range dynamics than habitat, especially at higher elevations. However, at mid-elevations SDMs showed an increasing importance of habitat on range shifts at these elevations, in the cases range shifts were reliably predicted. Predicting elevation range shifts on the basis of climate or habitat alone is insufficient, as habitat and climate play varying roles at different elevations, associated with different processes underlying range shifts. Failure to predict observed range shifts may arise from biotic interactions, behaviour flexibility, or evolutionary adaptation, aspects which are only beginning to be incorporated into distribution modelling frameworks.

Ocean currents modify the coupling between climate change and biogeographical shifts. Molinos JG, Burrows MT, and Poloczanska ES (2017). *Scientific Reports*, 7(1332). <http://dx.doi.org/10.1038/s41598-017-01309-y>

Geographic Location: Global

Type of Reference: Research Paper (Meta-Analysis)

Abstract: Biogeographical shifts are a ubiquitous global response to climate change. However, observed shifts across taxa and geographical locations are highly variable and only partially attributable to climatic conditions. Such variable outcomes result from the interaction between local climatic changes and other abiotic and biotic factors operating across species ranges. Among them, external directional forces such as ocean and air currents influence the dispersal of nearly all marine and many terrestrial



organisms. Here, using a global meta-dataset of observed range shifts of marine species, we show that incorporating directional agreement between flow and climate significantly increases the proportion of explained variance. We propose a simple metric that measures the degrees of directional agreement of ocean (or air) currents with thermal gradients and considers the effects of directional forces in predictions of climate-driven range shifts. Ocean flows are found to both facilitate and hinder shifts depending on their directional agreement with spatial gradients of temperature. Further, effects are shaped by the locations of shifts in the range (trailing, leading or centroid) and taxonomic identity of species. These results support the global effects of climatic changes on distribution shifts and stress the importance of framing climate expectations in reference to other non-climatic interacting factors.

Habitat compression and expansion of sea urchins in response to changing climate conditions on the California continental shelf and slope (1994-2013).

Sato KN, Levin LA, and Schiff K (2017). *Deep Sea Research Part II: Topical Studies in Oceanography*, **137**: 377-389. <http://dx.doi.org/10.1016/j.dsr2.2016.08.012>

Geographic Location: Southern California Bight, Pacific Ocean

Type of Reference: Research Paper

Abstract: Echinoid sea urchins with distributions along the continental shelf and slope of the eastern Pacific often dominate the megafauna community. This occurs despite their exposure to naturally low dissolved oxygen (DO) waters ($<60 \mu\text{mol kg}^{-1}$) associated with the Oxygen Limited Zone and low-pH waters undersaturated with respect to calcium carbonate ($\Omega_{\text{CaCO}_3} < 1$). Here we present vertical depth distribution and density analyses of historical otter trawl data collected in the Southern California Bight (SCB) from 1994 to 2013 to address the question: Do changes in echinoid density and species' depth distributions along the continental margin in the SCB reflect observed secular or interannual changes in climate? Deep-dwelling burrowing urchins (*Brissopsis pacifica*, *Brisaster* spp. and *Spatangus californicus*), which are adapted to low-DO, low-pH conditions appeared to have expanded their vertical distributions and populations upslope over the past decade (2003–2013), and densities of the deep pink urchin, *Strongylocentrotus fragilis*, increased significantly in the upper 500 m of the SCB. Conversely, the shallower urchin, *Lytechinus pictus*, exhibited depth shoaling and density decreases within the upper 200 m of the SCB from 1994 to 2013. Oxygen and pH in the SCB also vary inter-annually due to varying strengths of the El Niño Southern Oscillation (ENSO). Changes in depth distributions and densities were correlated with bi-monthly ENSO climate indices in the region. Our results suggest that both a secular trend in ocean deoxygenation and acidification and varying strength of ENSO may be linked to echinoid species distributions and densities, creating habitat compression in some and habitat expansion in others. Potential life-history mechanisms underlying depth and density changes observed over these time periods include migration, mortality, and recruitment. These types of analyses are needed for a broad suite of benthic species in order to identify and manage climate-sensitive species on the margin.



Phenology

Phenology is the timing of life-cycle events such as bird migration, breeding, and flowering. Changes in phenology have been linked to climate change in many parts of the world. Many ecological interactions among species can be affected by phenological mismatches as a result of differences in species' responses to changes in climate, leading to community- or ecosystem-level disruptions.

Climate change and timing of avian breeding and migration: evolutionary versus plastic changes. Charmantier A and Gienapp P (2014). *Evolutionary Applications*, 7(1): 15-28. <http://dx.doi.org/10.1111/eva.12126>

Geographic Location: Global

Type of Reference: Review Article

Abstract: There are multiple observations around the globe showing that in many avian species, both the timing of migration and breeding have advanced, due to warmer springs. Here, we review the literature to disentangle the actions of evolutionary changes in response to selection induced by climate change versus changes due to individual plasticity, that is, the capacity of an individual to adjust its phenology to environmental variables. Within the abundant literature on climate change effects on bird phenology, only a small fraction of studies are based on individual data, yet individual data are required to quantify the relative importance of plastic versus evolutionary responses. While plasticity seems common and often adaptive, no study so far has provided direct evidence for an evolutionary response of bird phenology to current climate change. This assessment leads us to notice the alarming lack of tests for microevolutionary changes in bird phenology in response to climate change, in contrast with the abundant claims on this issue. In short, at present we cannot draw reliable conclusions on the processes underlying the observed patterns of advanced phenology in birds. Rapid improvements in techniques for gathering and analysing individual data offer exciting possibilities that should encourage research activity to fill this knowledge gap.

Ecological and life history correlates of changes in avian migration timing in response to climate change. Bitterlin LR, and Van Buskirk J (2014). *Climate Research*, 61(2): 109-121. <http://dx.doi.org/10.3354/cr01238>

Geographic Location: Europe and North America

Type of Reference: Research Paper (Meta-Analysis)

Summary: Spring migration of birds in many parts of the world has advanced as the climate has become warmer. Variation in advancement among species has been



proposed to correlate with geography and life history features, but individual studies have reported variable results, and general patterns have been elusive. In a quantitative review of data from 389 bird species sampled at 69 European and 23 North American localities, we evaluated associations between change in the timing of migration and life history (body size, molt, broodedness), ecology (habitat, diet, nest position), and geography. We confirmed that spring migration advanced: -0.214 day yr⁻¹ (95% confidence interval: -0.266 , -0.162) for first- arriving individuals and -0.104 day yr⁻¹ (-0.139 , -0.071) for the meridian date of passage. The rate of change in autumn was more variable: 0.090 day yr⁻¹ (0.002 , 0.176) delay for median passage and 0.019 day yr⁻¹ (-0.175 , 0.204) delay for the date of last departure. The response during spring was weaker in the far north and in species that migrate long distances to the wintering area. Autumn migration became increasingly delayed in species that are large-bodied, molt before departure, and that feed on seeds, insects, or fruits. Variation among species, especially during autumn, was associated in part with constraints surrounding the timing of the postnuptial molt. The results suggest that ecological and life history features of species may influence their ability to respond to climate change.

Changes in breeding phenology and population size of birds. Dunn PO and Møller AP (2014). *Journal of Animal Ecology*, **83**(3): 729–739.
<http://dx.doi.org/10.1111/1365-2656.12162>

Geographic Location: Europe and North America
Type of Reference: Research Paper

Summary: Although the phenology of numerous organisms has advanced significantly in response to recent climate change, the life-history and population consequences of earlier reproduction remain poorly understood. We analyzed extensive data on temporal change in laying date and clutch size of birds from Europe and North America to test whether these changes were related to recent trends in population size. Across studies, laying date advanced significantly, while clutch size did not change. However, within populations, changes in laying date and clutch size were positively correlated, implying that species which advanced their laying date the most were also those that increased their clutch size the most. Greater advances in laying date were associated with species that had multiple broods per season, lived in nonagricultural habitats and were herbivorous or predatory. The duration of the breeding season increased for multibrooded species and decreased for single-brooded species. Changes in laying date and clutch size were not related to changes in population size (for resident or migratory species). This suggests that, across a wide variety of species, mismatches in the timing of egg laying or numbers of offspring have had relatively little influence on population size compared with other aspects of phenology and life history.



Drought-caused delay in nesting of Sonoran Desert birds and its facilitation of parasite- and predator-mediated variation in reproductive success. McCreedy C and van Riper III C (2015). *Auk*, **132**: 235-247. <http://dx.doi.org/10.1642/AUK-13-253.1>

Geographic Location: Southwestern United States

Type of Reference: Research Paper

Abstract: As our understanding of climate change has increased, so has our awareness of the impacts of these changes on biotic systems. Climate models are nearly unanimous in their predictions for increased drought frequency in southwestern North America, and delays in nest initiation due to drought may influence nesting success and productivity for many Sonoran Desert bird species. In southeastern California and western Arizona in 2004–2009, we found negative correlations for 13 of 13 species between nest initiation date and rainfall accumulation during the preceding 4-month winter rainy season. Nesting was delayed more than 3 weeks for some species during extreme droughts in 2006 and 2007. During 2004–2009, we found a significant negative effect of nest initiation date on nest survival probability ($\beta = -0.031 \pm 0.005$ SE, $P < 0.001$) for the four species of greatest sample size. To investigate the role of nesting delay in nesting success and productivity, in 2010 we conducted a manipulative experiment with Black-tailed Gnatcatchers (*Polioptila melanura*; BTGN) and Verdins (*Auriparus flaviceps*; VERD). Following a wet winter, we delayed clutch initiation dates for treatment pairs to match first-egg dates that we observed during droughts in 2006 and 2007. Nest initiation date had a significant negative effect on nest survival of both species (BTGN: $\beta = -1.18 \pm 0.27$ SE, $P < 0.001$; VERD: $\beta = -2.33 \pm 0.51$ SE, $P = 0.003$). Treatment pairs were unable to overcome the lost period of high productivity in March and early April, and had lower productivity than control pairs over the entire breeding season. As nest predation and Brown-headed Cowbird (*Molothrus ater*) parasitism were the most common causes of nest failure, we conclude that the impacts of climate change–caused drought on annual reproductive output in the Sonoran Desert will be further compounded by parasitism and predation for Black-tailed Gnatcatchers and by predation for Verdins.

Climate change and decadal shifts in the phenology of larval fishes in the California Current ecosystem. Asch RG (2015). *Proceedings of the National Academy of Sciences*, **112**(30): E4065-E4074. <http://dx.doi.org/10.1073/pnas.1421946112>

Geographic Location: California Current, Pacific Ocean

Type of Reference: Research Paper

Abstract: Climate change has prompted an earlier arrival of spring in numerous ecosystems. It is uncertain whether such changes are occurring in Eastern Boundary Current Upwelling ecosystems, because these regions are subject to natural decadal climate variability, and regional climate models predict seasonal delays in upwelling. To answer this question, the phenology of 43 species of larval fishes was investigated between 1951 and 2008 off southern California. Ordination of the fish community



showed earlier phenological progression in more recent years. Thirty-nine percent of seasonal peaks in larval abundance occurred earlier in the year, whereas 18% were delayed. The species whose phenology became earlier were characterized by an offshore, pelagic distribution, whereas species with delayed phenology were more likely to reside in coastal, demersal habitats. Phenological changes were more closely associated with a trend toward earlier warming of surface waters rather than decadal climate cycles, such as the Pacific Decadal Oscillation and North Pacific Gyre Oscillation. Species with long-term advances and delays in phenology reacted similarly to warming at the interannual time scale as demonstrated by responses to the El Niño Southern Oscillation. The trend toward earlier spawning was correlated with changes in sea surface temperature (SST) and mesozooplankton displacement volume, but not coastal upwelling. SST and upwelling were correlated with delays in fish phenology. For species with 20th century advances in phenology, future projections indicate that current trends will continue unabated. The fate of species with delayed phenology is less clear due to differences between Intergovernmental Panel on Climate Change models in projected upwelling trends.

Autumn, the neglected season in climate change research. Gallinat AS, Primack RB, and Wagner DL (2015). *Trends in Ecology & Evolution*, 30(3):169–176. <http://dx.doi.org/10.1016/j.tree.2015.01.004>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Autumn remains a relatively neglected season in climate change research in temperate and arctic ecosystems. This neglect occurs despite the importance of autumn events, including leaf senescence, fruit ripening, bird and insect migration, and induction of hibernation and diapause. Changes in autumn phenology alter the reproductive capacity of individuals, exacerbate invasions, allow pathogen amplification and higher disease-transmission rates, reshuffle natural enemy–prey dynamics, shift the ecological dynamics among interacting species, and affect the net productivity of ecosystems. We synthesize some of our existing understanding of autumn phenology and identify five areas ripe for future climate change research. We provide recommendations to address common pitfalls in autumnal research as well as to support the conservation and management of vulnerable ecosystems and taxa.

Migratory connectivity of Golden-crowned Sparrows from two wintering regions in California. Cormier RL, Humple DL, Gardali T, and Seavy N (2016). *Animal Migration*, 3(1): 48-56. <http://dx.doi.org/10.1515/ami-2016-0005>

Geographic Location: California

Type of Reference: Research Paper



Abstract: Knowledge of migratory connectivity is critical to understanding the consequences of habitat loss and climate change on migratory species. We used light-level geolocators to determine breeding locations and migratory routes of wintering Golden-crowned Sparrows (*Zonotrichia atricapilla*) in two regions of California, USA. Eight out of 9 birds tagged at coastal-wintering sites in Marin County went to breeding sites along the Gulf Coast of Alaska, while 7 out of 8 inland-wintering birds in Placer County migrated to interior sites in the Yukon, Northwest Territories, and British Columbia, Canada. Our estimate of the strength of migratory connectivity was relatively high ($r_m = 0.66$). Coastal-wintering birds followed a coastal migration route while inland-wintering birds migrated inland. Coastal wintering birds migrated significantly farther than inland birds (3,624 kilometers (km) versus 2,442 km). Coastal birds traveled at a greater rate during spring migration (179 km/day) than did inland birds (118 km/day), but there was no statistical difference in the rate of fall migration (167 km/d and 111 km/day, respectively). Dates of arrival and departure, and duration of spring and fall migration, did not differ between groups, nor did return rates. Rates of return also did not differ between tagged and control birds. The distinct migration routes and breeding areas suggests that there may be more structuring in the migratory geography of the Golden-crowned Sparrow than in a simple panmictic population.

Convergence of broad-scale migration strategies in terrestrial birds. La Sorte FA, Fink D, Hochachka WM, and Kelling S (2016). *Proceedings of the Royal Society B*, **283** (1823). <http://dx.doi.org/10.1098/rspb.2015.2588>.

Geographic Location: Western Hemisphere
Type of Reference: Research Paper

Abstract: Migration is a common strategy used by birds that breed in seasonal environments. Selection for greater migration efficiency is likely to be stronger for terrestrial species whose migration strategies require non-stop transoceanic crossings. If multiple species use the same transoceanic flyway, then we expect the migration strategies of these species to converge geographically towards the most optimal solution. We test this by examining population-level migration trajectories within the Western Hemisphere for 118 migratory species using occurrence information from eBird. Geographical convergence of migration strategies was evident within specific terrestrial regions where geomorphological features such as mountains or isthmuses constrained overland migration. Convergence was also evident for transoceanic migrants that crossed the Gulf of Mexico or Atlantic Ocean. Here, annual population-level movements were characterized by clockwise looped trajectories, which resulted in faster but more circuitous journeys in the spring and more direct journeys in the autumn. These findings suggest that the unique constraints and requirements associated with transoceanic migration have promoted the spatial convergence of migration strategies.



The combination of seasonal atmospheric and environmental conditions that has facilitated the use of similar broad-scale migration strategies may be especially prone to disruption under climate and land-use change.

Phenological shifts conserve thermal niches. Socolar JB, Epanchin PN, Beissinger SR, and Tingley MW (2017). *Proceedings of the National Academy of Sciences*, **114**(49): 12976-12981. <http://dx.doi.org/10.1073/pnas.1705897114>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Species respond to climate change in two dominant ways: range shifts in latitude or elevation and phenological shifts of life-history events. Range shifts are widely viewed as the principal mechanism for thermal niche tracking, and phenological shifts in birds and other consumers are widely understood as the principal mechanism for tracking temporal peaks in biotic resources. However, phenological and range shifts each present simultaneous opportunities for temperature and resource tracking, although the possible role for phenological shifts in thermal niche tracking has been widely overlooked. Using a canonical dataset of Californian bird surveys and a detectability-based approach for quantifying phenological signal, we show that Californian bird communities advanced their breeding phenology by 5–12 days over the last century. This phenological shift might track shifting resource peaks, but it also reduces average temperatures during nesting by over 1°Celsius, approximately the same magnitude that average temperatures have warmed over the same period. We further show that early-summer temperature anomalies are correlated with nest success in a continental-scale database of bird nests, suggesting avian thermal niches might be broadly limited by temperatures during nesting. These findings outline an adaptation surface where geographic range and breeding phenology respond jointly to constraints imposed by temperature and resource phenology. By stabilizing temperatures during nesting, phenological shifts might mitigate the need for range shifts. Global change ecology will benefit from further exploring phenological adjustment as a potential mechanism for thermal niche tracking and vice versa.

Temporal shifts and temperature sensitivity of avian spring migratory phenology: A phylogenetic meta-analysis. Usui T, Butchart SHM, and Phillimore AB (2017). *Journal of Animal Ecology*, **86**(2): 250-26. <http://dx.doi.org/10.1111/1365-2656.12612>

Geographic Location: Global

Type of Reference: Research Paper (Meta-Analysis)

Summary: There are wide reports of advances in the timing of spring migration of birds over time and in relation to rising temperatures, though phenological responses vary substantially within and among species. An understanding of the ecological, life-history



and geographic variables that predict this intra- and interspecific variation can guide our projections of how populations and species are likely to respond to future climate change.

Here, we conduct phylogenetic meta-analyses addressing slope estimates of the timing of avian spring migration regressed on (i) year and (ii) temperature, representing a total of 413 species across five continents. We take into account slope estimation error and examine phylogenetic, ecological and geographic predictors of intra- and interspecific variation. We confirm earlier findings that on average birds have significantly advanced their spring migration time by 2.1 days per decade and 1.2 days °C⁻¹. We find that over time and in response to warmer spring conditions, short-distance migrants have advanced spring migratory phenology by more than long-distance migrants. We also find that larger bodied species show greater advance over time compared to smaller bodied species. Our results did not reveal any evidence that interspecific variation in migration response is predictable on the basis of species' habitat or diet. We detected a substantial phylogenetic signal in migration time in response to both year and temperature, suggesting that some of the shifts in migratory phenological response to climate are predictable on the basis of phylogeny. However, we estimate high levels of species and spatial variance relative to phylogenetic variance, which is consistent with plasticity in response to climate evolving fairly rapidly and being more influenced by adaptation to current local climate than by common descent. On average, avian spring migration times have advanced over time and as spring has become warmer. While we are able to identify predictors that explain some of the true among-species variation in response, substantial intra- and interspecific variation in migratory response remains to be explained.

Increasing phenological asynchrony between spring green-up and arrival of migratory birds. Mayor SJ, Guralnick RP, Tingley, MW, Otegui J, Withey JC, et al. (2017). *Scientific Reports*, 7(1). <http://dx.doi.org/10.1038/s41598-017-02045-z>

Geographic Location: North America

Type of Reference: Research Paper

Summary: Consistent with a warming climate, birds are shifting the timing of their migrations, but it remains unclear to what extent these shifts have kept pace with the changing environment. Because bird migration is primarily cued by annually consistent physiological responses to photoperiod, but conditions at their breeding grounds depend on annually variable climate, bird arrival and climate-driven spring events would diverge. We combined satellite and citizen science data to estimate rates of change in phenological interval between spring green-up and migratory arrival for 48 breeding passerine species across North America. Both arrival and green-up changed over time, usually in the same direction (earlier or later). Although birds adjusted their arrival dates, 9 of 48 species did not keep pace with rapidly changing green-up and across all species the interval between arrival and green-up increased by over half a day per year. As green-up became earlier in the east, arrival of eastern breeding species increasingly



lagged behind green-up, whereas in the west—where green-up typically became later—birds arrived increasingly earlier relative to green-up. Our results highlight that phenologies of species and trophic levels can shift at different rates, potentially leading to phenological mismatches with negative fitness consequences.

Population abundance and ecological interactions

Many physiological processes are temperature- and water-dependent. Marine species are also influenced by physical factors associated with ocean processes such as the El Niño/Southern Oscillation and the Pacific Decadal Oscillation. Organisms may adapt to climate-related changes in temperature and water availability through migration to suitable habitats, changes in behavior such as in the timing of life-cycle events, or changes in morphology. Species unable to adapt to changing climate conditions may be at risk of significant population declines. In addition to the physical factors associated with climate, biological factors and interactions such as the availability of food or prey, diseases, and parasite infestations can affect growth, survival, reproduction and, ultimately, population size.

Terrestrial mammals

Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. Schloss CA, Nuñez TA, and Lawler JJ (2012). *Proceedings of the National Academy of Sciences*, **109**(22): 8606-8611.
<http://dx.doi.org/10.1073/pnas.116791109>

Geographic Location: Western Hemisphere

Type of Reference: Research Paper

Abstract: As they have in response to past climatic changes, many species will shift their distributions in response to modern climate change. However, due to the unprecedented rapidity of projected climatic changes, some species may not be able to move their ranges fast enough to track shifts in suitable climates and associated habitats. Here, we investigate the ability of 493 mammals to keep pace with projected climatic changes in the Western Hemisphere. We modeled the velocities at which species will likely need to move to keep pace with projected changes in suitable climates. We compared these velocities with the velocities at which species are able to move as a function of dispersal distances and dispersal frequencies. Across the Western Hemisphere, on average, 9.2% of mammals at a given location will likely be unable to keep pace with climate change. In some places, up to 39% of mammals may be unable to track shifts in suitable climates. Eighty-seven percent of mammalian species are expected to experience reductions in range size and 20% of these range reductions will likely be due to limited dispersal abilities as opposed to reductions in the area of suitable climate. Because climate change will likely outpace the response



capacity of many mammals, mammalian vulnerability to climate change may be more extensive than previously anticipated.

Population resilience in an American pika (*Ochotona princeps*) metapopulation.

Smith AT and Nagy JD (2015). *Journal of Mammalogy*, **96**(2): 394-404.

<http://dx.doi.org/10.1093/jmammal/gyv040>

Geographic Location: Bodie, California

Type of Reference: Research Paper

Abstract: Population resilience in a metapopulation of American pikas (*Ochotona princeps*) at Bodie, California, was investigated with a series of 18 detailed occupancy surveys conducted between 1989 and 2010. These were compared with earlier 1972 and 1977 censuses and earlier historical records of pikas at Bodie. There is concern that American pikas may be increasingly vulnerable to warm temperatures due to climate change, and this investigation represents the longest study of the species in a relatively low-elevation (warm) environment. The Bodie pika population represents one of the best mammalian examples of a classic metapopulation system. Annual number of observed patch extinctions (total = 114) and recolonizations (109) varied greatly among the 18 census intervals. There has been no decline in percent of patches occupied in the northern half of the study area since 1972, and the number of documented pikas in the north in recent surveys exceeded the numbers found in 1972 and 1977. In contrast, the southern half of the metapopulation collapsed during our study, apparently the result of stochasticity of metapopulation dynamics; no southern patches were occupied after 2006. The potential impact of temperature on metapopulation dynamics was examined using long-term chronic (average summer monthly maximum) and acute threshold (number of days $\geq 25^{\circ}\text{C}$ and $\geq 28^{\circ}\text{C}$ within a year) temperatures. There is no evidence that warming temperatures have directly and negatively affected pika persistence at Bodie. Neither warm chronic nor acute temperatures increased the frequency of extinctions of populations on patches, and relatively cooler chronic or acute temperatures did not lead to an increase in the frequency of recolonization events. Warm temperatures, however, could have impeded the dispersal of colonists moving from north to south, thus contributing to the failure of the southern region to become repopulated.

Thermal components of American Pika habitat—How does a small lagomorph encounter climate? Millar CI, Westfall R, and Delaney DL (2016). *Arctic Antarctic and Alpine Research*, **48**(2): 327-343. <http://dx.doi.org/10.1657/AAAR0015-046>

Geographic Location: Western United States

Type of Reference: Research Paper



Abstract: Anticipating the response of small mammals to climate change requires knowledge of thermal conditions of their habitat during times of the day and year when individuals use them. We measured diurnal and seasonal temperatures of free air and of six habitat components for American pikas (*Ochotona princeps*) over five years at 37 sites in seven mountain ranges in the western Great Basin, United States. Talus matrices (subsurfaces) had low daily variances and, in the warm season, remained cool during the hottest times of the day relative to surfaces and free air. During winter, matrices were warmer than free air. Talus surfaces were warmer than free air in the warm and cold seasons, and had large daily variances. Summer forefield and dispersal environments were warmest of all habitat components. Talus surfaces in summer were highly responsive to solar radiation over the course of the day, warming quickly to high midday temperatures, and cooling rapidly in the evening. By contrast, matrices lagged the daily warm-up and remained warmer than free air at night. These differences afford diurnal and seasonal opportunities for pikas to adapt behaviorally to unfavorable temperatures and suggest that animals can accommodate a wider range of future climates than has been assumed, although warming of the dispersal environment may become limiting. Climate envelope models that use or model only surface air measures and do not include information on individual thermal components of pika habitat may lead to errant conclusions about the vulnerability of species under changing climates.

American pikas (*Ochotona princeps*) extirpated from the historic masonic mining district of eastern California. Nichols LB, Klingler KB and Peacock MM (2016). *Western North American Naturalist*, **76**(2): 163-171.
<http://dx.doi.org/10.3398/064.076.0203>

Geographic Location: Eastern California
Type of Reference: Research Paper

Abstract: American pikas (*Ochotona princeps*) are small alpine lagomorphs and talus obligates with a narrow range of temperature tolerance, along with physiological and ecological characteristics that make them especially vulnerable to local extirpation in the face of climate change. Since their initial colonization of the Great Basin during the Pleistocene geological epoch, the distribution of pikas in this region has become more restricted, with population losses occurring especially in lower-elevation sites characterized by relatively low precipitation and high temperatures. Even where pikas have persisted, many populations are now restricted to higher elevations. We surveyed several sites in the Bodie Hills of eastern California known to have been recently occupied by pikas. Here we report the recent extirpations of 2 of these sites: one small cluster of anthropogenic patches in the historic Masonic Mining District and one natural patch on Masonic Mountain. These extirpations are consistent with those reported in California and across the Great Basin and may indicate the impending loss of pikas from this region due to impacts from global climate change.



Climate change refugia and habitat connectivity promote species persistence.

Morelli TL, Maher SP, Lim MCW, Kastely C, Eastman LM, et al. (2017). *Climate Change Responses*, 4:8. <http://dx.doi.org/10.1186/s40665-017-0036-5>

Geographic Location: Sierra Nevada, California

Type of Reference: Report

Abstract: *Background:* Climate change refugia, areas buffered from climate change relative to their surroundings, are of increasing interest as natural resource managers seek to prioritize climate adaptation actions. However, evidence that refugia buffer the effects of anthropogenic climate change is largely missing. *Methods:* Focusing on the climate-sensitive Belding's ground squirrel (*Urocitellus beldingi*), we predicted that highly connected Sierra Nevada meadows that had warmed less or shown less precipitation change over the last century would have greater population persistence, as measured by short-term occupancy, fewer extirpations over the twentieth century, and long-term persistence measured through genetic diversity. *Results:* Across California, *U. beldingi* were more likely to persist over the last century in meadows with high connectivity that were defined as refugial based on a suite of temperature and precipitation factors. In Yosemite National Park, highly connected refugial meadows were more likely to be occupied by *U. beldingi*. More broadly, populations inhabiting Sierra Nevada meadows with colder mean winter temperatures had higher values of allelic richness at microsatellite loci, consistent with higher population persistence in temperature-buffered sites. Furthermore, both allelic richness and gene flow were higher in meadows that had higher landscape connectivity, indicating the importance of metapopulation processes. Conversely, anthropogenic refugia, sites where populations appeared to persist due to food or water supplementation, had lower connectivity, genetic diversity, and gene flow, and thus might act as ecological traps. This study provides evidence that validates the climate change refugia concept in a contemporary context and illustrates how to integrate field observations and genetic analyses to test the effectiveness of climate change refugia and connectivity. *Conclusions:* Climate change refugia will be important for conserving populations as well as genetic diversity and evolutionary potential. Our study shows that in-depth modeling paired with rigorous fieldwork can identify functioning climate change refugia for conservation.

Birds and reptiles

Audubon's Birds and Climate Change Report: A Primer for Practitioners. National Audubon Society (2015). New York. Contributors: Langham G, Schuetz J, Soykan C, Wilsey C, Auer T, et al. Version 1.3.

http://climate.audubon.org/sites/default/files/NAS_EXTBIRD_V1.3_9.2.15%20lb.pdf

Geographic Location: North America

Type of Reference: Report



Abstract: The National Audubon Society has completed a continental analysis of how North America's birds may respond to future climate change. Using extensive citizen science data and detailed climate layers, we developed models that characterize the relationship between the distribution of each species and climate. Then, we used our models to forecast species distributions to future time periods based on climate estimates described by the Intergovernmental Panel on Climate Change (IPCC). This core set of analyses will serve as the backbone for informing bird conservation in North America through planning tools for land managers, reports focused on species of conservation concern, and peer-reviewed publications addressing the impacts of climate change on birds. We addressed three topics of general interest for broad-scale bird conservation, which we summarize here and on Audubon's website: (1) the impact of climate change on bird diversity in the United States and Canada (Part I); (2) identification of areas that are expected to remain important to birds under the present and future climate (Part II); and (3) in-depth analyses of potential climate change impacts on 314 species.

Seabirds as early warning indicators of climate events in the Pacific. Humphries G, Velarde E, Anderson DW, Haase B, and Sydeman WJ (2015). *PICES*, **23**(1).

Geographic Location: Pacific Ocean

Type of Reference: Review Article

Abstract: During the strong El Niños of 1982–83 and 1997–98, studies of marine life provided insight and foresight into the evolution and dissipation of these events. Top marine predators, such as seabirds, are particularly responsive to changes in oceanographic conditions during El Niño and other anomalous ocean conditions. In the past, changes in ocean temperature, stratification, currents and other physical factors have been associated with disruptions to coastal food webs, resulting in shifts in seabird distribution, changes in the timing of breeding and migration (phenology), reproductive failures, and even severe adult mortalities (e.g., massive seabird die-offs or “wrecks” observed on coastal beaches). Recently, sequential seabird observations from the Southern Hemisphere, progressing to the equatorial and central-north Pacific, suggest ecosystem impacts prior to an official declaration of an El Niño event in 2014–2015.

Spatial distribution and temporal patterns of cassin's auklet foraging and their euphausiid prey in a variable ocean climate. Manugian S, Elliott ML, Bradley R, Howar J, Karnovsky N, et al. (2015). *PLoS ONE*, **10**(12): e0144232.

<http://dx.doi.org/10.1371/journal.pone.0144232>.

Geographic Location: Gulf of the Farallones and Cordell Bank National Marines Sanctuary, California

Type of Reference: Research Paper



Abstract: Krill (Euphausiids) play a vital ecosystem role in many of the world's most productive marine regions, providing an important trophic linkage. We introduce a robust modeling approach to link Cassin's auklet (*Ptychoramphus aleuticus*) abundance and distribution to large-scale and local oceanic and atmospheric conditions and relate these patterns to similarly modeled distributions of an important prey resource, krill. We carried out at-sea strip transect bird surveys and hydroacoustic assessments of euphausiids (2004-2013). Data informed separate, spatially-explicit predictive models of Cassin's auklet abundance (zero-inflated negative binomial regression) and krill biomass (two-part model) based on these surveys. We established the type of prey responsible for acoustic backscatter by conducting net tows of the upper 50 meters (m) during surveys. We determined the types of prey fed to Cassin's auklet chicks by collecting diet samples from provisioning adults. Using time-depth-recorders, we found Cassin's auklets utilized consistent areas in the upper water column, less than 30 m, where krill could be found (99.5% of dives were less than 30 m). Birds primarily preyed upon two species of euphausiids, *Euphausia pacifica* and *Thysanoessa spinifera*, which were available in the upper water column. Cassin's auklet abundance was best predicted by both large scale and localized oceanic processes (upwelling) while krill biomass was best predicted by local factors (temperature, salinity, and fluorescence) and both large scale and localized oceanic processes (upwelling). Models predicted varying krill and bird distribution by month and year. Our work informs the use of Cassin's auklet as a valuable indicator of krill abundance and distribution and strengthens our understanding of the link between Cassin's auklet and its primary prey. We expect future increases in frequency and magnitude of anomalous ocean conditions will result in decreased availability of krill leading to declines in the Farallon Islands population of Cassin's auklets.

Foraging behavior links climate variability and reproduction in North Pacific albatrosses. Thorne LH, Hazen EL, Bograd S, Foley DG, Conners M, et al. (2015). *Movement Ecology*, 3: 27. <http://dx.doi.org/10.1186/s40462-015-0050-9>

Geographic Location: North Pacific Ocean

Type of Reference: Research Paper

Abstract: *Background:* Climate-driven environmental change in the North Pacific has been well documented, with marked effects on the habitat and foraging behavior of marine predators. However, the mechanistic linkages connecting climate-driven changes in behavior to predator populations are not well understood. We evaluated the effects of climate-driven environmental variability on the reproductive success and foraging behavior of Laysan and Black-footed albatrosses breeding in the Northwest Hawaiian Islands during both brooding and incubating periods. We assessed foraging trip metrics and reproductive success using data collected from 2002–2012 and 1981–2012, respectively, relative to variability in the location of the Transition Zone Chlorophyll Front (TZCF, an important foraging region for albatrosses), sea surface temperature (SST), Multivariate ENSO Index (MEI), and the North Pacific Gyre Oscillation index (NPGO). *Results:* Foraging behavior for both species was influenced



by climatic and oceanographic factors. While brooding chicks, both species traveled farther during La Niña conditions, when NPGO was high and when the TZCF was farther north (farther from the breeding site). Models showed that reproductive success for both species showed similar trends, correlating negatively with conditions observed during La Niña events (low MEI, high SST, high NPGO, increased distance to TZCF), but models for Laysan albatrosses explained a higher proportion of the variation. Spatial correlations of Laysan albatross reproductive success and SST anomalies highlighted strong negative correlations (>95 %) between habitat use and SST. Higher trip distance and/or duration during brooding were associated with decreased reproductive success. *Conclusions:* Our findings suggest that during adverse conditions (La Niña conditions, high NPGO, northward displacement of the TZCF), both Laysan and Black-footed albatrosses took longer foraging trips and/or traveled farther during brooding, likely resulting in a lower reproductive success due to increased energetic costs. Our results link climate variability with both albatross behavior and reproductive success, information that is critical for predicting how albatross populations will respond to future climate change.

Climate–ecosystem change off southern California: Time-dependent seabird predator–prey numerical responses. Sydeman WJ, Thompson SA, Santora JA, Koslow JA, Goericke R, and Ohman MD (2015). *Deep-Sea Research II*, **112**: 158-170. <http://dx.doi.org/10.1016/j.dsr2.2014.03.008>.

Geographic Location: Southern California
Type of Reference: Research Paper

Abstract: Climate change may increase both stratification and upwelling in marine ecosystems, but these processes may affect productivity in opposing or complementary ways. For the Southern California region of the California Current Ecosystem (CCE), we hypothesized that changes in stratification and upwelling have affected marine bird populations indirectly through changes in prey availability. To test this hypothesis, we derived trends and associations between stratification and upwelling, the relative abundance of potential prey including krill and forage fish, and seabirds based on the long-term, multidisciplinary CalCOFI/CCE-LTER program. Over the period 1987 through 2011, spring and summer seabird density (all species combined) declined by 2% per year, mostly in the northern sector of the study region. Krill showed variable trends with two species increasing and one decreasing, resulting in community reorganization. Nearshore forage fish, dominated by northern anchovy (*Engraulis mordax*) as well as offshore mesopelagic species, show declines in relative abundance over this period. The unidirectional decline in springtime seabird density is largely explained by declining nearshore fish abundance in the previous season (winter). Interannual variability in seabird density, especially in the 2000s, is explained by variability in krill abundance. Changes in the numerical responses of seabirds to prey abundance correspond to a putative ecosystem shift in 1998–1999 and support aspects of optimal foraging (diet) theory. Predator–prey interactions and numerical responses clearly explain aspects of



the upper trophic level patterns of change in the pelagic ecosystem off southern California.

Factors affecting the thermal environment of agassiz's desert tortoise (*Gopherus agassizii*) cover sites in the central mojave desert during periods of temperature extremes. Mack JS, Berry KH, Miller DM and Carlson AS (2015). *Journal of Herpetology*, 49(3): 405-414. <http://dx.doi.org/10.1670/13-080>

Geographic Location: Mojave Desert, California

Type of Reference: Research Paper

Abstract: Agassiz's Desert Tortoises (*Gopherus agassizii*) spend >95% of their lives underground in cover sites that serve as thermal buffers from temperatures, which can fluctuate >40°Celsius on a daily and seasonal basis. We monitored temperatures at 30 active tortoise cover sites within the Soda Mountains, San Bernardino County, California, from February 2004 to September 2006. Cover sites varied in type and structural characteristics, including opening height and width, soil cover depth over the opening, aspect, tunnel length, and surficial geology. We focused our analyses on periods of extreme temperature: in summer, between July 1 and September 1, and winter, between November 1 and February 15. With the use of multivariate regression tree analyses, we found cover-site temperatures were influenced largely by tunnel length and subsequently opening width and soil cover. Linear regression models further showed that increasing tunnel length increased temperature stability and dampened seasonal temperature extremes. Climate change models predict increased warming for southwestern North America. Cover sites that buffer temperature extremes and fluctuations will become increasingly important for survival of tortoises. In planning future translocation projects and conservation efforts, decision makers should consider habitats with terrain and underlying substrate that sustain cover sites with long tunnels and expanded openings for tortoises living under temperature extremes similar to those described here or as projected in the future.

Population trends for North American winter birds based on hierarchical models. Soykan CU, Sauer J, Schuetz JG, LeBaron GS, Dale K, and Langham GM (2016). *Ecosphere*, 7(5): e01351. <http://dx.doi.org/10.1002/ecs2.1351>

Geographic Location: North America

Type of Reference: Research Paper

Abstract: Managing widespread and persistent threats to birds requires knowledge of population dynamics at large spatial and temporal scales. For over 100 years, the Audubon Christmas Bird Count (CBC) has enlisted volunteers in bird monitoring efforts that span the Americas, especially southern Canada and the United States. We employed a Bayesian hierarchical model to control for variation in survey effort among



CBC circles and, using CBC data from 1966 to 2013, generated early-winter population trend estimates for 551 species of birds. Selecting a subset of species that do not frequent bird feeders and have $\geq 25\%$ range overlap with the distribution of CBC circles (228 species) we further estimated aggregate (i.e., across species) trends for the entire study region and at the level of states/provinces, Bird Conservation Regions, and Landscape Conservation Cooperatives. Moreover, we examined the relationship between ten biological traits—range size, population size, migratory strategy, habitat affiliation, body size, diet, number of eggs per clutch, age at sexual maturity, lifespan, and tolerance of urban/suburban settings—and CBC trend estimates. Our results indicate that 68% of the 551 species had increasing trends within the study area over the interval 1966–2013. When trends were examined across the subset of 228 species, the median population trend for the group was 0.9% per year at the continental level. At the regional level, aggregate trends were positive in all but a few areas. Negative population trends were evident in lower latitudes, whereas the largest increases were at higher latitudes, a pattern consistent with range shifts due to climate change. Nine of 10 biological traits were significantly associated with median population trend; however, none of the traits explained $>34\%$ of the deviance in the data, reflecting the indirect relationships between population trend estimates and species traits. Trend estimates based on the CBC are broadly congruent with estimates based on the North American Breeding Bird Survey, another large-scale monitoring program. Both of these efforts, conducted by citizen scientists, will be required going forward to ensure robust inference about population dynamics in the face of climate and land cover changes.

Brandt's cormorant diet (1994–2012) indicates the importance of fall ocean conditions for northern anchovy in central California. Elliot ML, Schmidt AE, Bradley R, Warzybok P, Sakuma KM, Field JC, and Jahncke J (2016). *Fisheries Oceanography*, 25(5): 515-528. <http://dx.doi.org/10.1111/fog.12169>

Geographic Location: Central California Coast
Type of Reference: Research Paper

Abstract: Effective ecosystem-based management requires a comprehensive understanding of the functional links in the system. In many marine systems, forage species constitute a critical link between primary production and upper trophic level marine predators. As top predators, seabirds can be indicators of the forage species they consume and the ocean processes that influence these populations. We analyzed the diet and breeding success for the years 1994, 2003, 2005, and 2007–2012 of the Brandt's cormorant (*Phalacrocorax penicillatus*), a piscivorous diving seabird, breeding in central California, to evaluate the extent to which cormorant diet composition relates to prey availability, and how diet composition relates to breeding success and ocean conditions. Cormorant diet was primarily composed of young-of-the-year (YOY) northern anchovy (*Engraulis mordax*), YOY rockfish (*Sebastes* spp.), and several species of small flatfish (order Pleuronectiformes). YOY rockfish consumption was positively related to their abundance as measured in a late spring pelagic midwater trawl survey. Northern anchovy appeared to be the most important prey as its



consumption was positively related to cormorant breeding success. More northern anchovy were consumed in years where warm-water conditions prevailed in the fall season before cormorant breeding. Thus, warm ocean conditions in the fall appear to be an important contributing factor in producing a strong year-class of northern anchovy in central California and consequently a strong-year class of Brandt's cormorant on the Farallon Islands.

Butterflies and other insects

Mountain pine beetle voltinism and life history characteristics across latitudinal and elevational gradients in the western United States. Bentz BJ, Vandygriff J, Jensen C, Coleman T, Maloney P, et al. (2014). *Forest Science*, **60**(3): 434–449. <http://dx.doi.org/10.5849/forsci.13-056>

Geographic Location: Western United States

Type of Reference: Research Paper

Abstract: Substantial genetic variation in development time is known to exist among mountain pine beetle (*Dendroctonus ponderosae* Hopkins) populations across the western United States. The effect of this variation on geographic patterns in voltinism (generation time) and thermal requirements to produce specific voltinism pathways have not been investigated. The influence of voltinism on fitness traits, body size, and sex ratio is also unclear. We monitored mountain pine beetle voltinism, adult body size, sex ratio, and air temperatures at sites across latitudinal and elevational gradients in the western United States. With the exception of two sites at the coolest and warmest locations, the number of days required to complete a generation was similar. Thermal units required to achieve a generation, however, were significantly less for individuals at the coolest sites. Evolved adaptations explain this pattern, including developmental rates and thresholds that serve to synchronize cohorts and minimize cold-sensitive life stages in winter. These same adaptations reduce the capacity of mountain pine beetle at the warmest sites to take full advantage of increased thermal units, limiting the capacity for bivoltinism within the current realized distribution. Temperature was not correlated with adult size and sex ratio, and size was greatest in host trees other than lodgepole pine (*Pinus contorta* Dougl.). Our results provide baseline information for evaluating population responses in a changing climate.

Global weather and local butterflies: Variable responses to a large-scale climate pattern along an elevational gradient. Pardikes NA, Shapiro AM, Dyer LA and Forister ML (2015). *Ecology*, **96**(11): 2891-2901. <http://dx.doi.org/10.1890/15-0661.1>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper



Abstract: Understanding the spatial and temporal scales at which environmental variation affects populations of plants and animals is an important goal for modern population biology, especially in the context of shifting climatic conditions. The El Niño Southern Oscillation (ENSO) generates climatic extremes of interannual variation, and has been shown to have significant effects on the diversity and abundance of a variety of terrestrial taxa. However, studies that have investigated the influence of such large-scale climate phenomena have often been limited in spatial and taxonomic scope. We used 23 years (1988–2010) of a long-term butterfly monitoring data set to explore associations between variation in population abundance of 28 butterfly species and variation in ENSO-derived sea surface temperature anomalies (SSTA) across 10 sites that encompass an elevational range of 2750 m in the Sierra Nevada mountain range of California. Our analysis detected a positive, regional effect of increased SSTA on butterfly abundance (wetter and warmer years predict more butterfly observations), yet the influence of SSTA on butterfly abundances varied along the elevational gradient, and also differed greatly among the 28 species. Migratory species had the strongest relationships with ENSO-derived SSTA, suggesting that large-scale climate indices are particularly valuable for understanding biotic-abiotic relationships of the most mobile species. In general, however, the ecological effects of large-scale climatic factors are context dependent between sites and species. Our results illustrate the power of long-term data sets for revealing pervasive yet subtle climatic effects, but also caution against expectations derived from exemplar species or single locations in the study of biotic-abiotic interactions.

Beyond annual and seasonal averages: Using temporal patterns of precipitation to predict butterfly richness across an elevational gradient. Badik K, Shapiro A, Bonilla MM, Jahner JP, Harrison JG, and Forister ML (2015). *Ecological Entomology*, 40(5): 585-595. <http://dx.doi.org/10.1111/een.12228>

Geographic Location: California

Type of Reference: Research Paper

Abstract: 1. Ecologists often make predictions about community richness and diversity using climate variables that include seasonal precipitation totals and mean daily temperatures. While means and totals can be effective predictors to a certain extent, the complexities of faunal–climate relationships might be oversimplified through the use of coarse-grained variables. 2. The goal of this study was to investigate less commonly studied climate variables, including indices of intra-annual variation in the timing and intensity of precipitation events that might be used to predict butterfly richness across an elevational gradient. Data from a long-term, single-observer dataset at four sites in California were examined with Bayesian model averaging and structural equation modelling. Species-specific responses to climate were compared with community responses at each site. 3. At lower elevations, it was found that the relative importance of climate variables shifted towards temporal patterns of precipitation, including the timing of the first storm event and the annual number of precipitation events. Heterogeneity among sites was apparent in the importance of specific weather



variables, and temporal trends (across years) were detected for a small number of variables. Species-specific results paralleled those obtained from analysis of species richness, thus suggesting a commonality of response to climate across site-specific assemblages. 4. Models were improved by inclusion of the Pacific Decadal Oscillation and El Niño-Southern Oscillation indices, indicating that regional variables can profitably be included in faunal–climate relationship analyses. These results emphasize the need for researchers to examine climate variables beyond the most readily summarized means and totals.

Understanding a migratory species in a changing world: Climatic effects and demographic declines in the western monarch revealed by four decades of intensive monitoring. Espeset AE, Harrison JG, Shapiro AM, Nice CC, Thorne JH, et al. (2016). *Oecologia*, **181**(3): 819-830. <http://dx.doi.org/10.1007/s00442-016-3600-y>

Geographic Location: Northern California
Type of Reference: Research Paper

Abstract: Migratory animals pose unique challenges for conservation biologists, and we have much to learn about how migratory species respond to drivers of global change. Research has cast doubt on the stability of the eastern monarch butterfly (*Danaus plexippus*) population in North America, but the western monarchs have not been as intensively examined. Using a Bayesian hierarchical model, sightings of western monarchs over approximately 40 years were investigated using summer flight records from ten sites along an elevational transect in Northern California. Multiple weather variables were examined, including local and regional temperature and precipitation. Population trends from the ten focal sites and a subset of western overwintering sites were compared to summer and overwintering data from the eastern migration. Records showed western overwintering grounds and western breeding grounds had negative trends over time, with declines concentrated early in the breeding season, which were potentially more severe than in the eastern population. Temporal variation in the western monarch also appears to be largely independent of (uncorrelated with) the dynamics in the east. For our focal sites, warmer temperatures had positive effects during winter and spring, and precipitation had a positive effect during spring. These climatic associations add to our understanding of biotic-abiotic interactions in a migratory butterfly, but shifting climatic conditions do not explain the overall, long-term, negative population trajectory observed in our data.

Soil fauna responses to natural disturbances, invasive species, and global climate change: Current state of the science and a call to action. Coyle DR, Nagendra UJ, Taylor MK, Campbell JH, Cunard CE, et al. (2017). *Soil Biology and Biochemistry*, **110**: 116-133. <http://dx.doi.org/10.1016/j.soilbio.2017.03.008>

Geographic Location: Global



Type of Reference: Review Article

Abstract: Environmental disturbances seem to be increasing in frequency and impact, yet we have little understanding of the belowground impacts of these events. Soil fauna, while widely acknowledged to be important drivers of biogeochemical function, soil structure and sustainability, and trophic interactions, are understudied compared to other belowground organisms such as archaea, bacteria, and fungi. In this review we summarize the current state of knowledge of soil fauna as it relates to and is influenced by various disturbances. We focus our review on three main natural and anthropogenic disturbance types: 1) natural disturbances, including damage from wind and flooding; 2) invasive species, including above and belowground flora and fauna; and 3) climate change impacts on the atmosphere and temperature. We do not address the impacts of wildfires, forestry, agricultural practices, mining, or human-caused pollution, as these topics have all been covered in other works. We highlight knowledge gaps and suggest future avenues of research, with hope that the importance of soil fauna and their influences on ecosystems will be given greater emphasis in future research.

Freshwater species

Climate change vulnerability of native and alien freshwater fishes of California: A systematic assessment approach. Moyle P, Kiernan JD, Crain PK, and Quinones R (2013). *PLOS One*, 8(5): e63883. <http://dx.doi.org/10.1371/journal.pone.0063883>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Freshwater fishes are highly vulnerable to human-caused climate change. Because quantitative data on status and trends are unavailable for most fish species, a systematic assessment approach that incorporates expert knowledge was developed to determine status and future vulnerability to climate change of freshwater fishes in California, USA. The method uses expert knowledge, supported by literature reviews of status and biology of the fishes, to score ten metrics for both (1) current status of each species (baseline vulnerability to extinction) and (2) likely future impacts of climate change (vulnerability to extinction). Baseline and climate change vulnerability scores were derived for 121 native and 43 alien fish species. The two scores were highly correlated and were concordant among different scorers. Native species had both greater baseline and greater climate change vulnerability than did alien species. Fifty percent of California's native fish fauna was assessed as having critical or high baseline vulnerability to extinction whereas all alien species were classified as being less or least vulnerable. For vulnerability to climate change, 82% of native species were classified as highly vulnerable, compared with only 19% for aliens. Predicted climate change effects on freshwater environments will dramatically change the fish fauna of California. Most native fishes will suffer population declines and become more restricted in their distributions; some will likely be driven to extinction. Fishes requiring cold water (<22°C) are particularly likely to go extinct. In contrast, most alien fishes will thrive, with



some species increasing in abundance and range. However, a few alien species will likewise be negatively affected through loss of aquatic habitats during severe droughts and physiologically stressful conditions present in most waterways during summer. Our method has high utility for predicting vulnerability to climate change of diverse fish species. It should be useful for setting conservation priorities in many different regions.

The thirsty eel: Summer and winter flow thresholds that tilt the Eel River of Northwestern California from salmon- supporting to cyanobacterially degraded states. Power ME, Bouma-Gregson K, Higgins P, et al. (2015). *Copeia*, **103**(1): 200- 11. <http://dx.doi.org/10.1643/CE-14-086>

Geographic Location: Eel River, California

Type of Reference: Review Article

Key Points: Although it flows through regions of northwestern California that are thought to be relatively well watered, the Eel River is increasingly stressed by drought and water withdrawals. We discuss how critical threshold changes in summer discharge can potentially tilt the Eel from a recovering salmon-supporting ecosystem toward a cyanobacterially degraded one. To maintain food webs and habitats that support salmonids and suppress harmful cyanobacteria, summer discharge must be sufficient to connect mainstem pools hydrologically with gently moving, cool base flow. Rearing salmon and steelhead can survive even in pools that become isolated during summer low flows if hyporheic exchange is sufficient. But if the ground water discharge that sustains river flow during summer drought drops below critical levels, warm stagnant conditions will kill salmonids, and cyanobacteria will thrive. Challenges and opportunities for restoring the Eel and increasing its resilience to climate extremes, water diversions, and excessive loading of fine sediments point toward exploring how land use and terrestrial vegetation affect delivery from uplands of water, heat, sediments, solutes, organic matter, and organisms—in ways that either heal or damage rivers.



Delta smelt: Life history and decline of a once-abundant species in the San Francisco estuary. Moyle PB, Brown LR, Durand JR, and Hobbs JA (2016). *San Francisco Estuary and Watershed*, 14(2).
<http://dx.doi.org/10.15447/sfews.2016v14iss2art6>

Geographic Location: San Francisco Estuary, California
Type of Reference: Review Article

Abstract: This paper reviews what has been learned about Delta Smelt and its status since the publication of *The State of Bay-Delta Science, 2008* (Healey et al., 2008). The Delta Smelt is endemic to the upper San Francisco Estuary. Much of its historic habitat is no longer available and remaining habitat is increasingly unable to sustain the population. As a listed species living in the central node of California's water supply system, Delta Smelt has been the focus of a large research effort to understand causes of decline and identify ways to recover the species. Since 2008, a remarkable record of innovative research on Delta Smelt has been achieved, which is summarized here. Unfortunately, research has not prevented the smelt's continued decline, which is the result of multiple, interacting factors. A major driver of decline is change to the Delta ecosystem from water exports, resulting in reduced outflows and high levels of entrainment in the large pumps of the South Delta. Invasions of alien species, encouraged by environmental change, have also played a contributing role in the decline. Severe drought effects have pushed Delta Smelt to record low levels in 2014–2015. The rapid decline of the species and failure of recovery efforts demonstrate an inability to manage the Delta for the “co-equal goals” of maintaining a healthy ecosystem and providing a reliable water supply for Californians. Diverse and substantial management actions are needed to preserve Delta Smelt.

Global patterns in lake ecosystem responses to warming based on the temperature dependence of metabolism. Kraemer BM, Chandra S, Dell AI, Dix M, Kuusisto E, et al. (2016). *Global Change Biology*, 23(5): 1881-1890.
<http://dx.doi.org/10.1111/gcb.13459>

Geographic Location: Global
Type of Reference: Research Paper

Abstract: Climate warming is expected to have large effects on ecosystems in part due to the temperature dependence of metabolism. The responses of metabolic rates to climate warming may be greatest in the tropics and at low elevations because mean temperatures are warmer there and metabolic rates respond exponentially to temperature (with exponents >1). However, if warming rates are sufficiently fast in higher latitude/elevation lakes, metabolic rate responses to warming may still be greater there even though metabolic rates respond exponentially to temperature. Thus, a wide range of global patterns in the magnitude of metabolic rate responses to warming could emerge depending on global patterns of temperature and warming rates. Here we use the Boltzmann–Arrhenius equation, published estimates of activation energy, and time



series of temperature from 271 lakes to estimate long-term (1970–2010) changes in 64 metabolic processes in lakes. The estimated responses of metabolic processes to warming were usually greatest in tropical/low-elevation lakes even though surface temperatures in higher latitude/elevation lakes are warming faster. However, when the thermal sensitivity of a metabolic process is especially weak, higher latitude/elevation lakes had larger responses to warming in parallel with warming rates. Our results show that the sensitivity of a given response to temperature (as described by its activation energy) provides a simple heuristic for predicting whether tropical/low-elevation lakes will have larger or smaller metabolic responses to warming than higher latitude/elevation lakes. Overall, we conclude that the direct metabolic consequences of lake warming are likely to be felt most strongly at low latitudes and low elevations where metabolism-linked ecosystem services may be most affected.

State of the Salmonids: Status of California's Emblematic Fishes 2017. Moyle PB, Lusardi RA, Samuel PJ, and Katz JVE (2017). UC Davis Center for Watershed Sciences. https://watershed.ucdavis.edu/files/biblio/SOS%20II_Final.pdf

Geographic Location: California

Type of Reference: Report

Abstract: California has, or had, 32 distinct kinds of salmonid fishes. They are either endemic to California or at the southern end of their ranges. Most are in serious decline: 45% and 74% of all salmonids will likely become extirpated from California in the next 50 and 100 years, respectively, if present trends continue. Our results suggest that California will lose more than half (52%) of its native anadromous salmonids and nearly a third (30%) of its inland taxa in just 50 years under current conditions. Climate change is a major overarching threat driving population declines throughout California and strongly affects the status of 84% of all salmonids reviewed. In addition, dams, agricultural operations, estuary alteration, non-native species, production hatcheries, and myriad other human-induced threats have contributed to declines. 81% of salmonids in California are now worse off than they were in 2007, when the previous version of this report was prepared. The changes in species status are the result of the 2012-2016 historic drought, improved data collection and review, and an improved understanding of climate change impacts. Returning these iconic species to sustainable levels requires access to productive and diverse habitats which promote the full range of life history diversity necessary to weather change. We recommend (i) protecting and investing in fully functioning watersheds such as the Smith River and Blue Creek, (ii) protecting and restoring source waters such as Sierra meadow systems, groundwater, and springs so that the impacts of climate change are reduced, (iii) restoring function and access to once productive and diverse habitats such as Central Valley floodplains, coastal lagoons, and estuaries, (iv) adopting reconciliation ecology as a basis for



management in human dominated landscapes, (v) improving habitat connectivity and passage to historical spawning and rearing habitat, and (vi) improving salmonid genetic management throughout California.

State of the Salmonids II: Fish in Hot Water. Status, Threats and Solutions for California Salmon, Steelhead, and Trout. University of California, Davis (2017).

Based on a report by Dr. Peter B. Moyle, Dr. Rob Lusardi, and Patrick Samuel, University of California, Davis and California Trout. <http://caltrout.org/wp-content/uploads/2017/05/SOS-II-Fish-in-Hot-Water-Report.pdf>

Geographic Location: California

Type of Reference: Report

In this State of the Salmonids II report we explore the following questions: What is the status of all California salmonids, both individually and collectively? What are major factors responsible for their present status, especially of declining species? How can California's salmonids be saved from extinction? Climate change was scored as a critical or high threat for 26 of 31 species (87%). It is the major, overarching anthropogenic threat affecting salmonids in California. Due to its high impact and importance to the long term survival of all salmonids in California, it is highlighted below. Climate change was scored a critical or high threat for a majority of species, and was considered a low threat to only one species.

Amphibian immunity—stress, disease, and climate change. Smith-Rollins LA (2017). *Development and Comparative Immunology*, **66**: 111-119.

<http://dx.doi.org/10.1016/j.dci.2016.07.002>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Like all other vertebrate groups, amphibian responses to the environment are mediated through the brain (hypothalamic)-pituitary-adrenal/interrenal (HPA/I) axis and the sympathetic nervous system. Amphibians are facing historically unprecedented environmental stress due to climate change that will involve unpredictable temperature and rainfall regimes and possible nutritional deficits due to extremes of temperature and drought. At the same time, amphibians in all parts of the world are experiencing unprecedented declines due to the emerging diseases, chytridiomycosis (caused by *Batrachochytrium dendrobatidis* and *Batrachochytrium salamandrivorans*) and ranavirus diseases due to viruses of the genus *Ranavirus* in the family Iridoviridae. Other pathogens and parasites also afflict amphibians, but here I will limit myself to a review of



recent literature linking stress and these emerging diseases (chytridiomycosis and ranavirus disease) in order to better predict how environmental stressors and disease will affect global amphibian populations.

Marine species

Regional extinction of a conspicuous dorid nudibranch (Mollusca: Gastropoda) in California. Goddard JHR, Hoover C, and Valdes A (2013). *Marine Biology*, **160**: 1497-1510. <http://dx.doi.org/10.1007/s00227-013-2204-x>

Geographic Location: Southern California

Type of Reference: Research Paper

Abstract: *Felimare californiensis* (= *Hypselodoris californiensis*) was once common throughout the Southern California Bight (SCB) and California Channel Islands. This well-known shallow-water nudibranch, which specializes on dysideid sponges, has persisted for decades in Mexico, but in California disappeared from its entire range by 1984. Since reappearing in 2003, it has been found only at Santa Catalina Island, plus sightings of single individuals in 2011 at Santa Cruz Island and San Diego. The decline of *F. californiensis* in California was documented using published historical records, museum collections, unpublished field accounts, and images posted online. The loss of this emblematic species is unique among Californian nudibranchs, including (1) its congener *Felimare porterae* (= *Mexichromis porterae*), with which it appears to overlap in diet, and (2) opisthobranch species with similar historical geographic ranges and mode of development. The decline in *F. californiensis* is not predicted by warming trends and climate variation over the past 40 years, including the strong El Niño events of 1983 and 1998. Coastal pollution from the large human population in southern California may have impacted *Dysidea ambliia*, the primary reported prey of *F. californiensis*. Historical overcollecting of the nudibranch and habitat loss through the development of major ports likely also contributed to its decline. Sightings since 2003 are consistent with a nascent recovery, as elements of water quality have improved in the SCB in recent decades.

Applied fisheries oceanography: Ecosystem indicators of ocean conditions inform fisheries management in the California Current. Peterson WT, Fisher JL, Peterson JO, Morgan CA, Burke BJ, and Fresh KL. (2014). *Oceanography*, **27**(4): 80–89. <http://dx.doi.org/10.5670/oceanog.2014.88>

Geographic Location: California Current, Pacific Ocean

Type of Reference: Review Article

Abstract: Fisheries oceanography is the study of ecological relationships between fishes and the dynamics of their marine environments and aims to characterize the physical, chemical, and biological factors that affect the recruitment and abundance of



harvested species. A recent push within the fisheries management community is toward ecosystem-based management. Here, we show how physical and biological oceanography data can be used to generate indicators of ocean conditions in an ecosystem context, and how these indicators relate to the recruitment of salmonids, sablefish, sardines, and rockfish in the California Current.

Climate change influences on marine infectious diseases: implications for management and society. Burge CA, Eakin CM, Friedman CS, Froelich B, Hershberger PK, Hofmann EE, et al. (2014). *Annual Review of Marine Science*, **6**: 249-277. <http://dx.doi.org/10.1146/annurev-marine-010213-135029>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Infectious diseases are common in marine environments, but the effects of a changing climate on marine pathogens are not well understood. Here we review current knowledge about how the climate drives host-pathogen interactions and infectious disease outbreaks. Climate-related impacts on marine diseases are being documented in corals, shellfish, finfish, and humans; these impacts are less clearly linked for other organisms. Oceans and people are inextricably linked, and marine diseases can both directly and indirectly affect human health, livelihoods, and well-being. We recommend an adaptive management approach to better increase the resilience of ocean systems vulnerable to marine diseases in a changing climate. Land-based management methods of quarantining, culling, and vaccinating are not successful in the ocean; therefore, forecasting conditions that lead to outbreaks and designing tools/approaches to influence these conditions may be the best way to manage marine disease.

Biological and physical ocean indicators predict the success of an invasive crab, *Carcinus maenas*, in the northern California Current. Yamada SB, Peterson WT, and Kosro PM (2015). *Marine Ecology Progress Series*, **537**:175-89. <http://dx.doi.org/10.3354/meps11431>

Geographic Location: Northern California Current

Type of Reference: Research Paper

Abstract: An introduced population of European green crabs *Carcinus maenas* was established in San Francisco Bay (California, USA) prior to 1989. Subsequently, their larvae were likely carried northward into the embayments of Oregon, Washington (USA), and British Columbia (Canada) by the unusually strong Davidson Current during the winter of the El Niño of 1997–1998. Since this colonizing event, green crabs in Oregon and Washington have persisted at low densities. In this study, we show that after the arrival of the strong founding year-class of 1998, significant recruitment to the Oregon and Washington populations has occurred, but only in 2003, 2005, 2006 and



2010. Warm winter water temperatures, high positive values of the Pacific Decadal Oscillation (PDO) and Multivariate ENSO (El Niño Southern Oscillation) indices in March, weak southward shelf currents in March and April, a late biological spring transition, and high abundance of subtropical copepods are all strongly correlated with strong year-classes. We hypothesize that northward transport of larvae from California by coastal currents during warm winters is the mechanism by which the larvae are delivered to the Pacific Northwest. Among the best indicators of northward flow (and green crab recruitment) were the date of 'biological spring transition', the sign of the PDO, and the biomass of southern copepod species, which indicate (1) stronger northward flow of coastal waters during winters, (2) relatively warm winters (sea surface temperature >10°C), which enable larvae to complete their development in the near-shore, and (3) coastal circulation patterns that may keep larvae close to shore, where they can be carried by tidal currents into estuaries to settle.

Climate change and marine vertebrates. Sydeman WJ, Poloczanska E, Reed TE, and Thompson SA (2015). *Science*, **350**(6262): 772-777.
<http://dx.doi.org/10.1126/science.aac9874>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Climate change impacts on vertebrates have consequences for marine ecosystem structures and services. We review marine fish, mammal, turtle, and seabird responses to climate change and discuss their potential for adaptation. Direct and indirect responses are demonstrated from every ocean. Because of variation in research foci, observed responses differ among taxonomic groups (redistributions for fish, phenology for seabirds). Mechanisms of change are (i) direct physiological responses and (ii) climate-mediated predator-prey interactions. Regional-scale variation in climate-demographic functions makes range-wide population dynamics challenging to predict. The nexus of metabolism relative to ecosystem productivity and food webs appears key to predicting future effects on marine vertebrates. Integration of climate, oceanographic, ecosystem, and population models that incorporate evolutionary processes is needed to prioritize the climate-related conservation needs for these species.

What changes in the carbonate system, oxygen, and temperature portend for the northeastern Pacific Ocean: A physiological perspective. Somero GN, Beers JM, Chan F, Hill TM, Klinger T, and Litvin SY (2015). *BioScience*, **66**(1): 14-26.
<http://dx.doi.org/10.1093/biosci/biv162>

Geographic Location: Northeast Pacific Ocean

Type of Reference: Review Article



Abstract: The northeastern Pacific Ocean is undergoing changes in temperature, carbonate chemistry, and dissolved oxygen concentration in concert with global change. Each of these stressors has wide-ranging effects on physiological systems, which may differ among species and life-history stages. Simultaneous exposure to multiple stressors may lead to even stronger impacts on organisms, but interacting effects remain poorly understood. Here, we examine how single- and multiple-stressor effects on physiology may drive changes in the behavior, biogeography, and ecosystem structure in coastal marine ecosystems, with emphasis on the California Current Large Marine Ecosystem. By analyzing the effects of stressors on physiological processes common to many marine taxa, we may be able to develop broadly applicable understandings of the effects of global change. This mechanistic foundation may contribute to the development of models and other decision-support tools to assist resource managers and policymakers in anticipating and addressing global change–driven alterations in marine populations.

Accounting for multiple pathways in the connections among climate variability, ocean processes, and coho salmon recruitment in the Northern California current. Mallick MJ, Cox SP, Peterman RM, Wainwright TC, and Peterson WT (2015). *Canadian Journal of Fisheries and Aquatic Sciences*, **72**(10): 1552-1564.
<http://dx.doi.org/10.1139/cjfas-2014-0509>

Geographic Location: Northern California Current, Pacific Ocean
Type of Reference: Research Paper

Abstract: Pathways linking climate to population dynamics of higher-trophic-level fish species such as Pacific salmon often involve a hierarchy in which regional-scale physical and biological processes mediate the effects of large-scale climate variability. We used probabilistic networks to investigate 17 potential ecological pathways linking climate to Oregon coho salmon (*Oncorhynchus kisutch*) recruitment. We found that pathways originating with the Pacific Decadal Oscillation were the most influential on recruitment, with the net effect being two to four times greater than for pathways originating with the North Pacific Gyre Oscillation or the Oceanic Niño Index. Among all environmental variables, sea surface temperature and an index of juvenile salmon prey biomass had the greatest effects on recruitment, with a 76% chance of recruitment being equal to or below average given that ocean temperatures were above average and a 34% chance of recruitment being below average given that prey biomass was above average. Our results provide evidence that shifts in climate patterns could strongly influence recruitment simultaneously through multiple ecological pathways and highlight the importance of quantifying cumulative effects of these pathways on higher-trophic-level species.



Estuarine fish communities respond to climate variability over both river and ocean basins. Feyrer F, Cloern JE, Brown LR, Fish MA, Hieb KA, and Baxter RD (2015). *Global Change Biology*, **21**(10): 3608-3619. <http://dx.doi.org/10.1111/gcb.12969>

Geographic Location: San Francisco Estuary, California

Type of Reference: Research Paper

Abstract: Estuaries are dynamic environments at the land–sea interface that are strongly affected by interannual climate variability. Ocean–atmosphere processes propagate into estuaries from the sea, and atmospheric processes over land propagate into estuaries from watersheds. We examined the effects of these two separate climate-driven processes on pelagic and demersal fish community structure along the salinity gradient in the San Francisco Estuary, California, USA. A 33-year data set (1980–2012) on pelagic and demersal fishes spanning the freshwater to marine regions of the estuary suggested the existence of five estuarine salinity fish guilds: limnetic (salinity=0–1), oligohaline (salinity=1–12), mesohaline (salinity=6–19), polyhaline (salinity=19–28), and euhaline (salinity=29–32). Climatic effects propagating from the adjacent Pacific Ocean, indexed by the North Pacific Gyre Oscillation (NPGO), affected demersal and pelagic fish community structure in the euhaline and polyhaline guilds. Climatic effects propagating over land, indexed as freshwater outflow from the watershed (OUT), affected demersal and pelagic fish community structure in the oligohaline, mesohaline, polyhaline, and euhaline guilds. The effects of OUT propagated further down the estuary salinity gradient than the effects of NPGO that propagated up the estuary salinity gradient, exemplifying the role of variable freshwater outflow as an important driver of biotic communities in river-dominated estuaries. These results illustrate how unique sources of climate variability interact to drive biotic communities and, therefore, that climate change is likely to be an important driver in shaping the future trajectory of biotic communities in estuaries and other transitional habitats.

Climate mediates hypoxic stress on fish diversity and nursery function at the land-sea interface. Hughes BB, Levey MD, Fountain MC, Carlisle AB, Chavez FP, and Gleason MG (2015). *Proceedings of the National Academy of Sciences of the United States of America*, **112**(26): 8025-8030. <http://dx.doi.org/10.1073/pnas.1505815112>

Geographic Location: Elkhorn Slough, Central California

Type of Reference: Research Paper

Abstract: Coastal ecosystems provide numerous important ecological services, including maintenance of biodiversity and nursery grounds for many fish species of ecological and economic importance. However, human population growth has led to increased pollution, ocean warming, hypoxia, and habitat alteration that threaten ecosystem services. In this study, we used long-term datasets of fish abundance, water quality, and climatic factors to assess the threat of hypoxia and the regulating effects of climate on fish diversity and nursery conditions in Elkhorn Slough, a highly eutrophic



estuary in central California (United States), which also serves as a biodiversity hot spot and critical nursery grounds for offshore fisheries in a broader region. We found that hypoxic conditions had strong negative effects on extent of suitable fish habitat, fish species richness, and abundance of the two most common flatfish species, English sole (*Parophrys vetulus*) and speckled sanddab (*Citharichthys stigmaeus*). The estuary serves as an important nursery ground for English sole, making this species vulnerable to anthropogenic threats. We determined that estuarine hypoxia was associated with significant declines in English sole nursery habitat, with cascading effects on recruitment to the offshore adult population and fishery, indicating that human land use activities can indirectly affect offshore fisheries. Estuarine hypoxic conditions varied spatially and temporally and were alleviated by strengthening of El Niño conditions through indirect pathways, a consistent result in most estuaries across the northeast Pacific. These results demonstrate that changes to coastal land use and climate can fundamentally alter the diversity and functioning of coastal nurseries and their adjacent ocean ecosystems.

The impact of El Niño events on the pelagic food chain in the northern California Current. Fisher JL, Peterson WT, and Rykaczewski RR (2015). *Global Change Biology*, 21(12): 4401-4414. <http://dx.doi.org/10.1111/gcb.13054>

Geographic Location: Northern California Current, Pacific Ocean

Type of Reference: Research Paper

Abstract: The zooplankton of the northern California Current are typically characterized by an abundance of lipid-rich copepods that support rapid growth and survival of ecologically, commercially, and recreationally valued fish, birds, and mammals. Disruption of this food chain and reduced ecosystem productivity are often associated with climatic variability such as El Niño events. We examined the variability in timing, magnitude, and duration of positive temperature anomalies and changes in copepod species composition in the northern California Current in relation to 10 tropical El Niño events. Measurable impacts on mesozooplankton of the northern California Current were observed during seven of 10 of these events. The occurrence of anomalously warm water and the response of the copepod community was rapid (lag of zero to 2 months) following the initiation of canonical Eastern Pacific (EP) events, but delayed (lag of 2–8 months) following ‘Modoki’ Central Pacific (CP) events. The variable lags in the timing of a physical and biological response led to impacts in the northern California Current peaking in winter during EP events and in the spring during CP events. The magnitude and duration of the temperature and copepod anomalies were strongly and positively related to the magnitude and duration of El Niño events, but were also sensitive to the phase of the lower frequency Pacific Decadal Oscillation. When fisheries managers and biological oceanographers are faced with the prospect of a future El Niño event, prudent management and observation will require consideration of



the background oceanographic conditions, the type of event, and both the magnitude and duration of the event when assessing the potential physical and biological impacts on the northern California Current.

Humpback whale diets respond to variance in ocean climate and ecosystem conditions in the California Current. Fleming AH, Clark CT, Calambokidis J, and Barlow J (2016). *Global Change Biology*, **22**(3): 1214-1224. <http://dx.doi.org/10.1111/gcb.13171>

Geographic Location: California Current, Pacific Ocean
Type of Reference: Research Paper

Abstract: Large, migratory predators are often cited as sentinel species for ecosystem processes and climate-related changes, but their utility as indicators is dependent upon an understanding of their response to environmental variability. Documentation of the links between climate variability, ecosystem change and predator dynamics is absent for most top predators. Identifying species that may be useful indicators and elucidating these mechanistic links provides insight into current ecological dynamics and may inform predictions of future ecosystem responses to climatic change. We examine humpback whale response to environmental variability through stable isotope analysis of diet over a dynamic 20-year period (1993–2012) in the California Current System (CCS). Humpback whale diets captured two major shifts in oceanographic and ecological conditions in the CCS. Isotopic signatures reflect a diet dominated by krill during periods characterized by positive phases of the North Pacific Gyre Oscillation (NPGO), cool sea surface temperature (SST), strong upwelling and high krill biomass. In contrast, humpback whale diets are dominated by schooling fish when the NPGO is negative, SST is warmer, seasonal upwelling is delayed and anchovy and sardine populations display increased biomass and range expansion. These findings demonstrate that humpback whales trophically respond to ecosystem shifts, and as a result, their foraging behavior is a synoptic indicator of oceanographic and ecological conditions across the CCS. Multi-decadal examination of these sentinel species thus provides insight into biological consequences of interannual climate fluctuations, fundamental to advancing ecosystem predictions related to global climate change.

Atmospheric rivers and the mass mortality of wild oysters: insight into an extreme future? Cheng BS, Chang AL, Deck A, and Ferner MC. (2016). *Proceedings of the Royal Society B*, **283**: 20161462. <http://dx.doi.org/10.1098/rspb.2016.1462>

Geographic Location: San Francisco Bay, California
Type of Reference: Research Paper

Abstract: Climate change is predicted to increase the frequency and severity of extreme events. However, the biological consequences of extremes remain poorly



resolved owing to their unpredictable nature and difficulty in quantifying their mechanisms and impacts. One key feature delivering precipitation extremes is an atmospheric river (AR), a long and narrow filament of enhanced water vapour transport. Despite recent attention, the biological impacts of ARs remain undocumented. Here, we use biological data coupled with remotely sensed and in situ environmental data to describe the role of ARs in the near 100% mass mortality of wild oysters in northern San Francisco Bay. In March 2011, a series of ARs made landfall within California, contributing an estimated 69.3% of the precipitation within the watershed and driving an extreme freshwater discharge into San Francisco Bay. This discharge caused sustained low salinities (less than 6.3) that almost perfectly matched the known oyster critical salinity tolerance and was coincident with a mass mortality of one of the most abundant populations throughout this species' range. This is a concern, because wild oysters remain a fraction of their historical abundance and have yet to recover. This study highlights a novel mechanism by which precipitation extremes may affect natural systems and the persistence of sensitive species in the face of environmental change.

Temporal variation in copepod abundance and composition in a strong, persistent coastal upwelling zone. Fontana RE, Elliot ML, Largier JL, and Jahncke J (2016). *Progress in Oceanography*, **142**: 1-16.
<http://dx.doi.org/10.1016/j.pocean.2016.01.004>.

Geographic Location: Gulf of the Farallones and Cordell Bank, California
Type of Reference: Research Paper

Abstract: Zooplankton abundance and species composition provide information on environmental variability in the ocean. While zooplankton time series span the west coast of North America, less data exist off north-central California. Here, we investigated a zooplankton time series, focusing specifically on copepods, collected within the Gulf of the Farallones–Cordell Bank area (37.5° to 38.5°N) from 2004 to 2009. Impacted by seasonally strong, persistent upwelling, this study area is located downstream of a major upwelling center (Point Arena). We found copepod abundance and species composition differed significantly, particularly between the first three years (2004–2006) and the latter three years (2007–2009) of the study. These changes were mainly observed as changes in abundance of boreal copepod species, *Pseudocalanus mimus* and *Acartia longiremis*. These taxa showed increasing abundances for the latter three years of the study (2007–2009). During the first three years of the time series, environmental measurements in the region showed lower alongshore wind stress, weaker upwelling, minimal surface alongshore flow, and warmer surface ocean temperatures. Temporal variations in copepod abundance and species composition correlated with several of these environmental measurements (e.g., surface cross-shore and alongshore flows, upwelling, and alongshore wind stress), indicating environmental forcing of primary consumers and ecosystem productivity in this strong, persistent upwelling zone.



Biological impacts of the 2013-2015 warm-water anomaly in the northeast Pacific: Winners, losers, and the future. Cavole LM, Demko AM, Diner RE, Giddings A, Koester I, Pagniello C, et al. (2016). *Oceanography*, **29**(2): 273-285.
<http://dx.doi.org/10.5670/oceanog.2016.32>

Geographic Location: Northeast Pacific Ocean

Type of Reference: Review Article

Abstract: A large patch of anomalously warm water (nicknamed “the Blob”) appeared off the coast of Alaska in the winter of 2013–2014 and subsequently stretched south to Baja California. This northeastern Pacific warm-water anomaly persisted through the end of 2015. Scientists and the public alike noted widespread changes in the biological structure and composition of both open-ocean and coastal ecosystems. Changes included geographical shifts of species such as tropical copepods, pelagic red crabs, and tuna; closures of commercially important fisheries; and mass strandings of marine mammals and seabirds. The ecological responses to these physical changes have been sparsely quantified and are largely unknown. Here, we provide a bottom-up summary of some of the biological changes observed in and around the areas affected by the Blob.

Age- and sex-specific survival of California sea lions (*Zalophus californianus*) at San Miguel Island, California. DeLong RL, Melin SR, Laake JL, Morris P, Orr AJ, and Harris JD (2017). *Marine Mammal Science*, **33**(4): 1097-1125.
<http://dx.doi.org/10.1111/mms.12427>

Geographic Location: San Miguel Island, California

Type of Reference: Research Paper

Abstract: We conducted a mark-recapture study of California sea lions (*Zalophus californianus*) using pups branded on San Miguel Island, California, from 1987 to 2014, and annual resightings from 1990 to 2015. We used the Burnham model (Burnham 1993), an extension of the Cormack-Jolly-Seber mark-recapture model, which includes recoveries of dead animals, to analyze age, sex, and annual patterns in survival. Generally, females had higher survival than males. For female pups, the average annual survival was 0.600 and for male pups it was 0.574. Yearling survival was 0.758 and 0.757 for females and males, respectively. Peak annual survival was at age 5 and was 0.952 for females and 0.931 for males. Pups with larger mass at branding had higher survival as pups and yearlings, but the effect was relative within each cohort because of large between-cohort variability in survival. Annual variability in sea surface temperature (SST) affected survival. For each 1°C increase in SST, the odds of survival decreased by nearly 50% for pups and yearlings; negative SST anomalies yielded higher survival. Annual variation in male survival was partly explained by leptospirosis outbreaks. Our study provides a unique view of one demographic parameter that contributed to the successful recovery of the California sea lion population.



Influence of climate on the biodiversity and community structure of fishes in the southern California Current. Koslow JA, McMonagle H, and Watson W (2017). *Marine Ecology Progress Series*, **571**: 193-206. <http://dx.doi.org/10.3354/meps12095>

Geographic Location: Southern California Current, Pacific Ocean

Type of Reference: Research Paper

Abstract: Previous studies have reported dramatic declines of midwater fishes in the southern California Current System (CCS) in response to reduced deepwater oxygen concentration, and many CCS endemics and cool-water affinity taxa have also declined since 1969. Here we show that these abundance changes are associated with changes in the diversity of the CCS fish community. Species richness was positively associated with periods of relatively high midwater oxygen concentration and with the warm phase of the Pacific Decadal Oscillation, the multivariate ENSO index, and warmer near-surface temperature. While the decline of CCS endemics and cool-water affinity taxa was not associated with a change in species richness, it significantly enhanced the evenness of the fish community by markedly reducing the abundance of dominant taxa. Community structure overall, however, changed relatively little: the rank order of the 15 most abundant taxa changed little between periods of high and low species richness and evenness. Overall, fish community structure in the CCS thus appears to have remained stable in recent decades, despite marked changes in abundance of entire suites of species and significant changes in several biological diversity indices. The increase in the Shannon-Wiener index of evenness associated with the marked decline of several dominant taxa in the CCS indicates that changes in simple diversity indices need to be interpreted cautiously: increased diversity cannot be equated with improved ecosystem functioning.

Population growth and status of California sea lions. Laake JL, Lowry MS, DeLong RL, Melin SR, and Carretta JV (2018). *Journal of Wildlife Management*, **82**(1). <http://dx.doi.org/10.1002/jwmg.21405>

Geographic Location: Pacific coast of the United States (including southeast Alaska) and Canada

Type of Reference: Research Paper

Abstract: The California sea lion (*Zalophus californianus*) population in the United States has increased steadily since the early 1970s. The Marine Mammal Protection Act of 1972 (MMPA) established criteria for management of marine mammals based on the concept of managing populations within the optimal sustainable population (OSP), defined as arrange of abundance from the maximum net productivity level (MNPL) to carrying capacity (K). Recent declines in California sea lion pup production and survival suggest that the population may have stopped growing, but the status of the population relative to OSP and MNPL is unknown. We used a time series of pup counts from 1975 to 2014 and a time series of mark-release-resight-recovery data from 1987 to 2015 for survival estimates to numerically reconstruct the population



and evaluate the current population status relative to OSP using a generalized logistic model. We demonstrated that the population size in 2014 was above MNPL and within its OSP range. However, we also showed that population growth can be dramatically decreased by increasing sea surface temperature associated with El Nino events or similar regional ocean temperature anomalies. In this analysis of the population dynamics and a scientific foundation upon which to base management decisions related to complex resource issues involving this species.

Impacts on vegetation

Like animals, plant species have unique requirements for climate and environmental conditions. Globally, a growing number of studies have demonstrated plant responses to changing climatic conditions. Such responses include: changes in the timing of life-cycle events (such as blooming); changes in range boundaries or the distribution of the population within their ranges (generally to higher elevations or latitudes); and changes in species abundance. The recent California drought highlighted the impacts of a warming climate and moisture deficits on vegetation, manifested in changes in the structure and composition of forests and woodlands.

The papers addressing impacts on plants are grouped below under three separate headings: agricultural crops, forests and woodlands – including wildfires, and aquatic vegetation (in general).

Agricultural crops

California produces nearly half of the fruits, nuts and vegetables grown in the United States and purchased across the nation. Agricultural crops can be affected by changes in temperature, CO₂ levels and precipitation. Warming may affect crop yields both beneficially (as a result, for example, of the lengthening of the growing season) and adversely (for example, due to a reduction in the magnitude and length of winter chill needed for fruit and nut production). Warmer temperatures and increased humidity may also promote the growth of weeds, insects and fungi that can adversely impact crop production. Finally, crop damage can result from extremes in heat, frost or precipitation.

A biologically based approach to modeling spring phenology in temperate deciduous trees. Pope KS, Brown PH, DeJong TM, and Da Silva D (2014). *Forest Meteorology*, 198: 15-23. <http://dx.doi.org/10.1016/j.agrformet.2014.07.009>

Geographic Location: California

Type of Reference: Research Paper



Description: Prediction of the timing of spring phenological events such as bloom and leaf-out has important uses in agricultural and ecological management and modeling. However, after decades of model comparison there remains no consensus model to predict the date of spring phenological events in perennial temperate trees across species and locations. This lack of consensus may be due to over-fitting resulting from high model complexity, use of parameters that have not been adequately validated, or omission of parameters that are sound biological indicators of dormancy breaking. The aim of this study was to construct spring phenology candidate models with biologically-based parameters and starting values to test hypotheses regarding chill accumulation duration and the impact of pre-bloom conditions. Bloom data for three cultivars of *Prunus dulcis* (almond) from three decades in California were analyzed. Across all three cultivars, models which accumulated chill until approximately 75% of the heat requirement had been met, and did not integrate pre-bloom conditions, were substantially supported by the data. This suggests cold temperatures affect dormancy breaking well after the chilling requirement has been met and bud break timing is not substantially impacted by environmental conditions just prior to bud break. Fitting spring phenology using biologically based starting values estimated from bud break records may allow for the development of improved predictive models and improved approximations of critical phenological thresholds.

Nut crop yield records show that budbreak-based chilling requirements may not reflect yield decline chill thresholds. Pope KS, Dose V, Da Silva D, Brown PH, and DeJong TM (2014). *International Journal of Biometeorology*, 59(6): 707-715.
<http://dx.doi.org/10.1007/s00484-014-0881-x>

Geographic Location: Central Valley, California
Type of Reference: Research Paper

Abstract: Warming winters due to climate change may critically affect temperate tree species. Insufficiently cold winters are thought to result in fewer viable flower buds and the subsequent development of fewer fruits or nuts, decreasing the yield of an orchard or fecundity of a species. The best existing approximation for a threshold of sufficient cold accumulation, the “chilling requirement” of a species or variety, has been quantified by manipulating or modeling the conditions that result in dormant bud breaking. However, the physiological processes that affect budbreak are not the same as those that determine yield. This study sought to test whether budbreak-based chilling thresholds can reasonably approximate the thresholds that affect yield, particularly regarding the potential impacts of climate change on temperate tree crop yields. County-wide yield records for almond (*Prunus dulcis*), pistachio (*Pistacia vera*), and walnut (*Juglans regia*) in the Central Valley of California were compared with 50 years of weather records. Bayesian nonparametric function estimation was used to model yield potentials at varying amounts of chill accumulation. In almonds, average yields occurred when chill accumulation was close to the budbreak-based chilling requirement. However, in the other two crops, pistachios and walnuts, the best previous estimate of the budbreak-based chilling requirements was 19–32 % higher than the chilling



accumulations associated with average or above average yields. This research indicates that physiological processes beyond requirements for budbreak should be considered when estimating chill accumulation thresholds of yield decline and potential impacts of climate change.

Temperature increase reduces global yields of major crops in four independent estimates. Zhao C, Liu B, Piao S, Wang X, Lobell DBet al. (2017) *Proceedings of the National Academy of Sciences*, **114**(35): 9326-9331.
<http://dx.doi.org/10.1073/pnas.1701762114>

Geographic Location: Global

Type of Reference: Research paper

Abstract: Wheat, rice, maize, and soybean provide two-thirds of human caloric intake. Assessing the impact of global temperature increase on production of these crops is therefore critical to maintaining global food supply, but different studies have yielded different results. Here, we investigated the impacts of temperature on yields of the four crops by compiling extensive published results from four analytical methods: global grid-based and local point-based models, statistical regressions, and field-warming experiments. Results from the different methods consistently showed negative temperature impacts on crop yield at the global scale, generally underpinned by similar impacts at country and site scales. Without carbon dioxide (CO₂) fertilization, effective adaptation, and genetic improvement, each degree-Celsius increase in global mean temperature would, on average, reduce global yields of wheat by 6.0%, rice by 3.2%, maize by 7.4%, and soybean by 3.1%. Results are highly heterogeneous across crops and geographical areas, with some positive impact estimates. Multimethod analyses improved the confidence in assessments of future climate impacts on global major crops and suggest crop- and region-specific adaptation strategies to ensure food security for an increasing world population.

Forests and woodlands

Recent studies have documented changes to the structure and composition of California's forested lands and woodlands and examined the influence of altered precipitation patterns and increased temperatures on these changes. Examples include tree deaths, elevational changes in species distributions, increased dominance of hardwoods in historically conifer-dominated forests, and larger, more severe wildfires and longer fire seasons.



Widespread shifts in the demographic structure of subalpine forests in the Sierra Nevada, California. Dolanc CR, Thorne JH, and Safford HD (2013). *Global Ecology and Biogeography*, 22: 264–276. <http://dx.doi.org/10.1111/j.1466-8238.2011.00748.x>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Abstract: *Aim:* Many climate-linked vegetation models predict major contraction of subalpine forests within the next 100 years, which would require a relatively rapid replacement of high-elevation species by lower-elevation species over large portions of subalpine forest. We tested this prediction by comparing empirical data from a historic data set with data collected from re-sampled sites from 2007–09. *Location:* Central Sierra Nevada, CA, USA, 2300–3400 meter (m) elevation. *Methods:* We re-sampled 139 undisturbed historical vegetation plots across 5500 square kilometers (km²) originally sampled from 1929–34 in the subalpine zone of the Sierra Nevada, and compared historical with current forest structure and composition. We compared historic and modern climatic conditions using two high-elevation climate stations nearby. *Results:* Subalpine forests experienced a net increase in tree stem density of 30.4%, including a 63.3% increase in small trees. Six of eight tree species showed statistically significant increases in small tree density, including species with distributions at both the upper and lower boundaries of subalpine. Increases in small tree density were partly offset by a 20% decrease in large trees. These shifts were significant throughout the landscape of our study area. Modern stand composition was indistinguishable from historical composition. Daily minimum temperature (+ 1.2°Celsius) and precipitation (+ 15–48%) both increased during the same period. *Main conclusions:* Warming temperatures plus steady to increasing precipitation have led to less stressful conditions for recruitment and survival of small trees, and are probably contributing to increased mortality of large trees. Tree abundance and composition in the subalpine has not changed in the direction predicted by vegetation models linked to future climate scenarios. Our results underline the fundamental role that moisture balance plays in structuring mediterranean-zone montane forests. Future shifts in vegetation composition and structure from these regions are likely to depend on interactions between water balance and disturbance factors like fire, insects and disease.

Changing forest structure across the landscape of the Sierra Nevada, CA, USA, since the 1930s. Dolanc CR, Safford HD, Thorne JH, and Dobrowski SZ (2014). *Ecosphere*, 5(8): 1-26. <http://dx.doi.org/10.1890/ES14-00103.1>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Abstract: Understanding the dynamics of forest structure aids inference regarding future forests and their distributions around the world. Over the last few decades, several papers have addressed changing forest structure in the Sierra Nevada, CA,



USA, but these studies were limited in scope. We carried out a broad comparison of forest density and composition in the 1930s versus the 2000s for the west slope of the central and northern Sierra Nevada, using the two most extensive data sets available. Forests in this region have endured a long, complex history of human disturbance, and are now experiencing climatic shifts. We subdivided the landscape into elevation and latitude zones and compared historical and modern tree densities within each zone. We compared densities in historical plots to burned and unburned modern plots, as well as densities of individual tree species in historical vs. modern plots for their entire elevational distribution. Density of small trees (10.2–30.4 cm dbh) was significantly higher in the modern data set for all elevations and all latitudes, ranging from 20 to 148% higher. However, density of large trees (≥ 61.0 cm) was lower in the modern data set for most elevations and latitudes, ranging from 41% to 60% lower in most zones. Density difference of mid-sized trees (30.5–60.9 cm) was mixed, but was generally higher in modern plots. The pattern of more small trees but fewer large trees held for most individual species as well, but with notable exceptions. Our comparison of burned and unburned plots strongly implicates fire suppression as a driver of increased density of small trees in low- to mid-elevation forests. However, modern high-elevation (>2500 m) forests, where fire suppression impacts should be minimal, were also significantly denser than historical plots. Changing climatic conditions may be driving increased densities of small trees in high elevations, as well as decreased densities of large trees across the region.

Evidence of tree species' range shifts in a complex landscape. Monleon VJ and Lintz HE (2015). PLoS ONE, **10**(1): e0118069.
<http://dx.doi.org/10.1371/journal.pone.0118069>

Geographic Location: Western United States
Type of Reference: Research Paper

Abstract: Climate change is expected to change the distribution of species. For long-lived, sessile species such as trees, tracking the warming climate depends on seedling colonization of newly favorable areas. We compare the distribution of seedlings and mature trees for all but the rarest tree species in California, Oregon and Washington, United States of America, a large, environmentally diverse region. Across 46 species, the mean annual temperature of the range of seedlings was 0.120°Celsius colder than that of the range of trees (95% confidence interval from 0.096 to 0.144°Celsius). The extremes of the seedling distributions also shifted towards colder temperature than those of mature trees, but the change was less pronounced. Although the mean elevation and mean latitude of the range of seedlings was higher than and north of those of the range of mature trees, elevational and latitudinal shifts run in opposite directions for the majority of the species, reflecting the lack of a direct biological relationship between species' distributions and those variables. The broad scale, environmental diversity and variety of disturbance regimes and land uses of the study area, the large number and exhaustive sampling of tree species, and the direct causal



relationship between the temperature response and a warming climate, provide strong evidence to attribute the observed shifts to climate change.

Vegetation cover change in the Upper Kings River basin of the Sierra Nevada detected using Landsat satellite image analysis. Potter C (2015). *Climatic Change*, 131(4): 635-647. <http://dx.doi.org/10.1007/s10584-015-1397-z>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Abstract: The Sierra Nevada of California is a region where large forest fires have been suppressed for over a century and future climate warming has the potential to alter vegetation cover and surface water runoff. A detailed geographic record of recent changes in vegetation cover across the Sierra Nevada remains a gap that can be filled with satellite remote sensing data. Results from Landsat image analysis over the past 25 years in the Upper Kings River basin showed that consistent increases in the normalized difference vegetation index (NDVI) have not extended above 2000 meters elevation. Moreover, mean increases in NDVI since 1986 at elevations below 2000 meters (which cover about half of the total basin area) have not exceeded 9 %, even in the most extreme precipitation yearly comparisons. NDVI has decreased significantly at elevations above 2000 meters throughout the basin in relatively wet year comparisons since the mid-1980s. These findings conflict with any assumptions that evapotranspiration fluxes impacting river flows downstream have been altered mainly by vegetation change over most of the Upper Kings River basin in recent decades.

Tree mortality from drought, insects, and their interactions in a changing climate. Anderegg WRL, Hicke JA, Fisher RA, Allen CD, Aukema J, et al. (2015). *New Phytologist*, 208: 674-683. <http://dx.doi.org/10.1111/nph.13477>

Geographic Location: Western United States

Type of Reference: Review Article

Abstract: Climate change is expected to drive increased tree mortality through drought, heat stress, and insect attacks, with manifold impacts on forest ecosystems. Yet, climate-induced tree mortality and biotic disturbance agents are largely absent from process-based ecosystem models. Using data sets from the western USA and associated studies, we present a framework for determining the relative contribution of drought stress, insect attack, and their interactions, which is critical for modeling mortality in future climates. We outline a simple approach that identifies the mechanisms associated with two guilds of insects – bark beetles and defoliators – which are responsible for substantial tree mortality. We then discuss cross-biome patterns of insect-driven tree mortality and draw upon available evidence contrasting the prevalence of insect outbreaks in temperate and tropical regions. We conclude with an



overview of tools and promising avenues to address major challenges. Ultimately, a multitrophic approach that captures tree physiology, insect populations, and tree–insect interactions will better inform projections of forest ecosystem responses to climate change.

Morphological and physiological phenology of *Pinus longaeva* in the White Mountains of California. Hallman C and Arnott H (2015). *Tree-Ring Research*, 71(1): 1-12. <http://dx.doi.org/10.3959/1536-1098-71.1.1>

Geographic Location: White Mountains, California

Type of Reference: Research Paper

Abstract: Natural variations and responses to climate change can be identified within climatically sensitive ecosystems by monitoring growing season events. In 1962–1964, Fritts conducted a phenologic study on *Pinus longaeva* in the White Mountains of California. He monitored growing season events, environmental data, and dendrometer readings. In this study morphological and physiological phenophases, dendrometer traces, and environmental data were collected throughout the summers of 2007 and 2008 in the White Mountains of California to better understand variability in *Pinus longaeva* phenology and identify any shifts in the growing season since the 1962–1964 study (Fritts 1969). As a result of a late-season snow storm, observable phenophases in 2008 were 12 days later than in 2007. Pollination onset was slightly earlier than in the 1962–1964, which may indicate that accumulated heat or a combination of environmental factors influence these phenophases. Duration and timing of cambial activity in the present study was similar to that recorded in the Fritts (1969) investigation despite a median summer temperature increase of at least 2°Celsius.

Species-specific phenological responses to winter temperature and precipitation in a water-limited ecosystem. Mazer SJ, Gerst KL, Matthews ER and Evenden A (2015). *Ecosphere*, 6(6): 1-27. <http://dx.doi.org/10.1890/ES14-00433.1>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Phenology is the study of seasonal biological events such as flowering, leaf-out, insect emergence, and animal migration. Long-term observational studies at numerous temperate zone sites have found that the timing of phenological events responds to temporal variation in climate. To assess the phenological effects of climatic variation on California's flora, The California Phenology Project (CPP) was established in 2010 to develop and to test monitoring protocols and to create tools to support long-term phenological monitoring and education in several California national parks. The CPP uses standardized protocols developed in collaboration with the USA National Phenology Network (USA-NPN) to track the phenological status of 30 plant species



across key environmental gradients (e.g., latitude, elevation, and precipitation). To date, over 860K phenological records collected by trained citizen scientists, natural resource managers, and park interns participating in the CPP have been contributed to the National Phenology Database. Observations recorded up to twice per week during the first 40 months of monitoring by the CPP were of sufficiently high resolution to detect associations between local climatic conditions and the onset of targeted phenophases. Here, we present analyses of four of the most intensively-monitored species: *Baccharis pilularis* (Asteraceae), *Quercus lobata* (Fagaceae), *Sambucus nigra* (Caprifoliaceae), and *Eriogonum fasciculatum* (Polygonaceae). We examined the effects of monthly climate parameters during a four month window (December to March), including mean minimum temperatures (Tmin), total monthly precipitation, and their interactions, on the onset dates of four phenophases per species. Stepwise regressions explained a high proportion (30–99%) of the variation in the onset date of each phenophase. Species and phenophases differed, however, with respect to the strength and the direction of the relationship between each month's conditions (Tmin and/or precipitation) and the timing of vegetative and reproductive phenophases. Given the high climatic variation represented among the monitored sites and among years (2011–2013), it was possible to detect significant associations between local, recent winter conditions and the onset dates of subsequent phenophases, although interactions between monthly conditions were also common. These patterns permit preliminary predictions regarding how these species will respond to future winter warming and intensifying drought.

Temperate forest health in an era of emerging megadisturbance. Millar CI and Stephenson NL (2015). *Science*, **349**(6250): 823-826.
<http://dx.doi.org/10.1126/science.aaa9933>.

Geographic Location: Global

Type of Reference: Review Article

Abstract: Although disturbances such as fire and native insects can contribute to natural dynamics of forest health, exceptional droughts, directly and in combination with other disturbance factors, are pushing some temperate forests beyond thresholds of sustainability. Interactions from increasing temperatures, drought, native insects and pathogens, and uncharacteristically severe wildfire are resulting in forest mortality beyond the levels of 20th-century experience. Additional anthropogenic stressors, such as atmospheric pollution and invasive species, further weaken trees in some regions. Although continuing climate change will likely drive many areas of temperate forest toward large-scale transformations, management actions can help ease transitions and minimize losses of socially valued ecosystem services.



On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Allen CD, Breshears DD, and McDowell NG (2015). *Ecosphere*, 6(8): 129. <http://dx.doi.org/10.1890/ES15-00203.1>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Patterns, mechanisms, projections, and consequences of tree mortality and associated broad-scale forest die-off due to drought accompanied by warmer temperatures—“hotter drought”, an emerging characteristic of the Anthropocene—are the focus of rapidly expanding literature. Despite recent observational, experimental, and modeling studies suggesting increased vulnerability of trees to hotter drought and associated pests and pathogens, substantial debate remains among research, management and policy-making communities regarding future tree mortality risks. We summarize key mortality-relevant findings, differentiating between those implying lesser versus greater levels of vulnerability. Evidence suggesting lesser vulnerability includes forest benefits of elevated [CO₂] and increased water-use efficiency; observed and modeled increases in forest growth and canopy greening; widespread increases in woody-plant biomass, density, and extent; compensatory physiological, morphological, and genetic mechanisms; dampening ecological feedbacks; and potential mitigation by forest management. In contrast, recent studies document more rapid mortality under hotter drought due to negative tree physiological responses and accelerated biotic attacks. Additional evidence suggesting greater vulnerability includes rising background mortality rates; projected increases in drought frequency, intensity, and duration; limitations of vegetation models such as inadequately represented mortality processes; warming feedbacks from die-off; and wildfire synergies. Grouping these findings we identify ten contrasting perspectives that shape the vulnerability debate but have not been discussed collectively. We also present a set of global vulnerability drivers that are known with high confidence: (1) droughts eventually occur everywhere; (2) warming produces hotter droughts; (3) atmospheric moisture demand increases nonlinearly with temperature during drought; (4) mortality can occur faster in hotter drought, consistent with fundamental physiology; (5) shorter droughts occur more frequently than longer droughts and can become lethal under warming, increasing the frequency of lethal drought nonlinearly; and (6) mortality happens rapidly relative to growth intervals needed for forest recovery. These high-confidence drivers, in concert with research supporting greater vulnerability perspectives, support an overall viewpoint of greater forest vulnerability globally. We surmise that mortality vulnerability is being discounted in part due to difficulties in predicting threshold responses to extreme climate events. Given the profound ecological and societal implications of underestimating global vulnerability to hotter drought, we highlight urgent challenges for research, management, and policy-making communities.



Climate-driven diversity loss in a grassland community. Harrison SP, Gornish ES and Copeland S (2015). *Proceedings of the National Academy of Sciences of the United States of America*, **112**(28): 8672-8677.

<http://dx.doi.org/10.1073/pnas.1502074112>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Local ecological communities represent the scale at which species coexist and share resources, and at which diversity has been experimentally shown to underlie stability, productivity, invasion resistance, and other desirable community properties. Globally, community diversity shows a mixture of increases and decreases over recent decades, and these changes have relatively seldom been linked to climatic trends. In a heterogeneous California grassland, we documented declining plant diversity from 2000 to 2014 at both the local community (5 square meters (m²)) and landscape (27 km²) scales, across multiple functional groups and soil environments. Communities became particularly poorer in native annual forbs, which are present as small seedlings in midwinter; within native annual forbs, community composition changed toward lower representation of species with a trait indicating drought intolerance (high specific leaf area). Time series models linked diversity decline to the significant decrease in midwinter precipitation. Livestock grazing history, fire, succession, N deposition, and increases in exotic species could be ruled out as contributing causes. This finding is among the first demonstrations to our knowledge of climate-driven directional loss of species diversity in ecological communities in a natural (nonexperimental) setting. Such diversity losses, which may also foreshadow larger-scale extinctions, may be especially likely in semiarid regions that are undergoing climatic trends toward higher aridity and lower productivity.

Progressive forest canopy water loss during the 2012-2015 California drought.

Asner GP, Brodrick PG, Anderson CB, Vaughn N, Knapp DE, and Martin RE (2015). *Proceedings of the National Academy of Sciences*, **113**(2): E249-E255.

<http://dx.doi.org/10.1073/pnas.1523397113>

Geographic Location: California

Type of Reference: Research Paper

Abstract: The 2012–2015 drought has left California with severely reduced snowpack, soil moisture, ground water, and reservoir stocks, but the impact of this estimated millennial-scale event on forest health is unknown. We used airborne laser-guided spectroscopy and satellite-based models to assess losses in canopy water content of California's forests between 2011 and 2015. Approximately 10.6 million hectares (ha) of forest containing up to 888 million large trees experienced measurable loss in canopy water content during this drought period. Severe canopy water losses of greater than 30% occurred over 1 million ha, affecting up to 58 million large trees. Our measurements exclude forests affected by fire between 2011 and 2015. If drought



conditions continue or reoccur, even with temporary reprieves such as El Niño, we predict substantial future forest change.

Landsat image analysis of tree mortality in the southern Sierra Nevada region of California during the 2013-2015 drought. Potter C (2016). *Journal of Earth Science & Climatic Change*, 7: 342. <http://dx.doi.org/10.4172/2157-7617.1000342>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Abstract: The United States Forest Service (USFS) observed marked increases in tree mortality in the southern Sierra Nevada foothills and mountains of California using aerial monitoring surveys in April 2015. Aircraft flew over 4 million acres of forested land and found that about 20 percent of forest stands had detectable mortality, totaling 10.45 million dead trees. In this study, Landsat satellite imagery was analyzed at over 90% of these high tree mortality sites in the southern Sierra to understand how the three consecutive years (2013-2015) of extreme drought conditions compared to changes in forest stand growth rates dating to the mid-1980s across this region. Results showed that changes in Landsat drought sensitive indices from the years 2011 to 2015 closely matched patterns of tree mortality across USFS April 2015 aerial survey locations in the southern Sierra Nevada. The historically low snow year of 2015 could have essentially reset the average forest canopy density for many forests in the region to late 1980s levels, due to drought-related mortality, combined with numerous large stand-replacing wildfires. The corresponding patterns and trends in Landsat drought sensitive indices with observed tree mortality rates can better inform region-wide assessments of forest growth trends and enable long-term drought impact monitoring.

The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. Clark JS, Iverson L, Woodall CW, Allen CD, Bell DM, et al. (2016). *Global Change Biology*, 22(7): 2329-2352. <http://dx.doi.org/10.1111/gcb.13160>

Geographic Location: United States

Type of Reference: Review Article

Abstract: We synthesize insights from current understanding of drought impacts at stand-to-biogeographic scales, including management options, and we identify challenges to be addressed with new research. Large stand-level shifts underway in western forests already are showing the importance of interactions involving drought, insects, and fire. Diebacks, changes in composition and structure, and shifting range limits are widely observed. In the eastern US, the effects of increasing drought are becoming better understood at the level of individual trees, but this knowledge cannot yet be confidently translated to predictions of changing structure and diversity of forest stands. While eastern forests have not experienced the types of changes seen in



western forests in recent decades, they too are vulnerable to drought and could experience significant changes with increased severity, frequency, or duration in drought. Throughout the continental United States, the combination of projected large climate-induced shifts in suitable habitat from modeling studies and limited potential for the rapid migration of tree populations suggests that changing tree and forest biogeography could substantially lag habitat shifts already underway. Forest management practices can partially ameliorate drought impacts through reductions in stand density, selection of drought-tolerant species and genotypes, artificial regeneration, and the development of multistructured stands. However, silvicultural treatments also could exacerbate drought impacts unless implemented with careful attention to site and stand characteristics. Gaps in our understanding should motivate new research on the effects of interactions involving climate and other species at the stand scale and how interactions and multiple responses are represented in models. This assessment indicates that, without a stronger empirical basis for drought impacts at the stand scale, more complex models may provide limited guidance.

Thirty years of vegetation change in the coastal Santa Cruz Mountains of Northern California detected using landsat satellite image analysis. Potter C (2016). *Journal of Coastal Conservation*, **20**(1): 51-59.
<http://dx.doi.org/10.1007%2Fs11852-015-0417-5>

Geographic Location: Santa Cruz Mountains, California
Type of Reference: Research Paper

Abstract: The Santa Cruz Mountains is a coastal landscape with a history of extensive forest logging, and a future with projected climate warming that may alter vegetation cover and surface water runoff in new ways. Results from Landsat satellite image time-series analysis since 1983 of this study area showed gradual, statistically significant increases in the normalized difference vegetation index (NDVI) in more than 90 % of the (predominantly second-growth) evergreen forest locations sampled. The cumulative distribution of NDVI values in 2013 was significantly different and higher overall from the cumulative distribution of NDVI values in 1983. The extreme drought year of 2013 (and other previous years of low precipitation) did not affect average NDVI growth rates in most drainage basins of the study area, with the exception of four relatively small basins that had less than 30 % forested land cover. Notably different patterns of NDVI change were detected in areas burned by wildfires in recent years. Within the perimeters of the 2008 Summit Fire and the 2009 Lockheed Fire, NDVI showed notable declines from pre-fire levels to those calculated in 2013 Landsat imagery. In contrast to these recent fires, the burned area from the 1985 Lexington Fire showed the highest rate of NDVI increase (over 27 years of regrowth) of any relatively large contiguous area within the Santa Cruz Mountains.



Thirty year analysis of forest and scrub canopy cover on the Big Sur coast of California using Landsat Imagery. Potter C (2016). *Journal of Ecosystem and Ecography*, 6(3): 199. <http://dx.doi.org/10.4172/2157-7625.1000199>

Geographic Location: Big Sur, California

Type of Reference: Research Paper

Abstract: The Santa Cruz Mountains is a coastal landscape with a history of extensive forest logging, and a future with projected climate warming that may alter vegetation cover and surface water runoff in new ways. Results from Landsat satellite image time-series analysis since 1983 of this study area showed gradual, statistically significant increases in the normalized difference vegetation index (NDVI) in more than 90 % of the (predominantly second-growth) evergreen forest locations sampled. The cumulative distribution of NDVI values in 2013 was significantly different and higher overall from the cumulative distribution of NDVI values in 1983. The extreme drought year of 2013 (and other previous years of low precipitation) did not affect average NDVI growth rates in most drainage basins of the study area, with the exception of four relatively small basins that had less than 30 % forested land cover. Notably different patterns of NDVI change were detected in areas burned by wildfires in recent years. Within the perimeters of the 2008 Summit Fire and the 2009 Lockheed Fire, NDVI showed notable declines from pre-fire levels to those calculated in 2013 Landsat imagery. In contrast to these recent fires, the burned area from the 1985 Lexington Fire showed the highest rate of NDVI increase (over 27 years of regrowth) of any relatively large contiguous area within the Santa Cruz Mountains.

California's historic legacy for landscape change, the Wieslander Vegetation Type Maps. Thorne JH and Le TN (2016). *Madroño*, 63(4): 293-328. <http://dx.doi.org/10.3120/0024-9637-63.4.293>

Geographic Location: California

Type of Reference: Research Paper

Abstract: This paper presents the digitized edition of the Wieslander Vegetation Type Maps (VTMs). The VTMs were part of the first statewide systematic survey of California's vegetation, conducted 1928–1939. Under the direction of Albert Wieslander, crews recorded the patterns of vegetation that they observed from vantage points across the state. The survey covers 176,901 square kilometers (km²) including border and lake polygons and 165,652 km² of landscapes that we describe in more detail. There are 251,541 polygons in the full extent of the maps, with 249,630 in the analysis extent. These polygons are annotated with codes indicating the dominant plant species, for which voucher specimens were collected. The maps contain 655 species codes, representing 535 species or sub-species in 229 genera, including 34 *Arctostaphylos* Adans. and 16 *Quercus* L. species. The 249,630 polygons contain 26,013 unique combinations of species and levels of disturbance. These can be classified into 525 vegetation alliances or provisional alliances using the 2009 edition of the Manual of



California Vegetation, or into 53 of the simpler California Wildlife Habitat Relationships (WHR) classes. The most extensive WHR types in the VTMs are Annual grasslands (25,733 km²) Chamise-redshank chaparral (14,771 km²), Mixed chaparral (9314 km²), and Coastal Scrub (7088 km²). California's Southwestern ecoregion is the most completely surveyed, with 93% of the area mapped, followed by the Central Western ecoregion (88.2%, including the Bay Area), the Sierra Nevada (71.6%), and the Great Valley (39.7%). The VTMs in these ecoregions provide a baseline for assessment of landcover change across large areas, and are an important legacy of the biogeographic patterns of plants and vegetation in California. This paper provides the methods used to digitize the collection and suggestions about how the data may be properly used in future studies.

Climate and bark beetle effects on forest productivity—linking dendroecology with forest landscape modeling. Kretchun AM, Loudermilk LE, Scheller RM, Hurteau MD, and Belmecheri S (2016). *Canadian Journal of Forest Research*, **46**(8): 1026-1034. <http://dx.doi.org/10.1139/cjfr-2016-0103>

Geographic Location: California and Nevada/Lake Tahoe Basin
Type of Reference: Research Paper

Abstract: In forested systems throughout the world, climate influences tree growth and aboveground net primary productivity (ANPP). The effects of extreme climate events (i.e., drought) on ANPP can be compounded by biotic factors (e.g., insect outbreaks). Understanding the contribution of each of these influences on growth requires information at multiple spatial scales and is essential for understanding regional forest response to changing climate. The mixed conifer forests of the Lake Tahoe Basin, California and Nevada, provide an opportunity to analyze biotic and abiotic influences on ANPP. Our objective was to evaluate the influence of moisture stress (climatic water deficit, CWD) and bark beetles on basin-wide ANPP from 1987 to 2006, estimated through tree core increments and a landscape simulation model (LANDIS-II). Tree ring data revealed that ANPP increased throughout this period and had a nonlinear relationship to water demand. Simulation model results showed that despite increased complexity, simulations that include moderate moisture sensitivity and bark beetle outbreaks most closely approximated the field-derived ANPP~CWD relationship. Although bark beetle outbreaks and episodic drought-induced mortality events are often correlated, decoupling them within a simulation model offers insight into assessing model performance, as well as examining how each contributes to total declines in productivity.



Defense traits in the long-lived Great Basin bristlecone pine and resistance to the native herbivore mountain pine beetle. Bentz BJ, Hood SM, Hansen EM, Vandygriff JC, and Mock KE (2016). *New Phytologist*, **213**(2): 611-624.
<http://dx.doi.org/10.1111/nph.14191>

Geographic Location: Western United States

Type of Reference: Research Paper

Summary: Mountain pine beetle (MPB, *Dendroctonus ponderosae*) is a significant mortality agent of Pinus, and climate-driven range expansion is occurring. Pinus defenses in recently invaded areas, including high elevations, are predicted to be lower than in areas with longer term MPB presence. MPB was recently observed in high-elevation forests of the Great Basin (GB) region, North America. Defense and susceptibility in two long-lived species, GB bristlecone pine (*Pinus longaeva*) and foxtail pine (*P.balfouriana*), are unclear, although they are sympatric with a common MPB host, limber pine (*P.flexilis*).

We surveyed stands with sympatric GB bristlecone–limber pine and foxtail–limber pine to determine relative MPB attack susceptibility and constitutive defenses.

MPB-caused mortality was extensive in limber, low in foxtail and absent in GB bristlecone pine. Defense traits, including constitutive monoterpenes, resin ducts and wood density, were higher in GB bristlecone and foxtail than in limber pine.

GB bristlecone and foxtail pines have relatively high levels of constitutive defenses which make them less vulnerable to climate-driven MPB range expansion relative to other high-elevation pines. Long-term selective herbivore pressure and exaptation of traits for tree longevity are potential explanations, highlighting the complexity of predicting plant–insect interactions under climate change.

California forests show early indications of both range shifts and local persistence under climate change. Serra-Diaz JM, Franklin J, Dillon WW, Syphard AD, Davis FW and Meentemeyer RK (2016). *Global Ecology and Biogeography*, **25**(2): 164-175. <http://dx.doi.org/10.1111/geb.12396>

Geographic Location: California

Type of Reference: Research Paper

Abstract: *Aim:* Forest regeneration data provide an early signal of the persistence and migration of tree species, so we investigated whether species shifts due to climate change exhibit a common signal of response or whether changes vary by species. *Location:* California Floristic Province, United States; mediterranean biome. *Methods:* We related Forest Inventory and Analysis (FIA) data from 2000–07 for 13 tree species to high-resolution climate and geographical data. Using methods from invasion ecology, we derived indices of species-specific regeneration overlap and central tendency



change (range-wide global indicators) based on kernel density estimation of presence and absence of regeneration. We then built regeneration surfaces to identify areas of occurrence of high regeneration (regeneration hotspots, local indicators) in both geographical and climate space for 13 common tree species. *Results:* Differences between presence and absence of regeneration in forests varied in magnitude across species, with little evidence that tree regeneration is shifting to higher latitudes and elevations, the expected geographical fingerprint of climate change. We also identified potential topographic mediators of regeneration dynamics. Multiple regeneration hotspots were found for many species, suggesting the influence of non-climatic factors on regeneration. Differences between the presence and absence of regeneration in geographic and climate spaces were not always congruent, suggesting that shifting climate space and range area are not entirely coupled. *Main conclusions:* The distributions of regeneration in Californian forests show diverse signals, not always tracking the higher latitudinal–elevation fingerprint of climate change. Local regeneration hotspots are common in our analysis, suggesting spatially varying persistence of forest linked to natural and anthropogenic disturbances. Our results emphasize that projections of tree range shifts in the context of climate change should consider the variation of regeneration drivers within species ranges, beyond the overall climate signal.

Ecological effects of extreme drought on Californian herbaceous plant communities. Copeland SM, Harrison SP, Latimer A, Damschen E, Eskelinen A, et al. (2016). *Ecological Monographs*, **86**(3): 295-311. <http://dx.doi.org/10.1002/ecm.1218>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Understanding the consequences of extreme climatic events is a growing challenge in ecology. Climatic extremes may differentially affect varying elements of biodiversity, and may not always produce ecological effects exceeding those of "normal" climatic variation in space and time. We asked how the extreme drought years of 2013-2014 affected the cover, species richness, functional trait means, functional diversity, and phylogenetic diversity of herbaceous plant communities across the California Floristic Province. We compared the directions and magnitudes of these drought effects with expectations from four "pre-drought" studies of variation in water availability: (1) a watering experiment, (2) a long-term (15-yr) monitoring of interannual variability, (3) a resampling of historic (57-yr-old) plots within a warming and drying region, and (4) natural variation in communities over a broad geographic gradient in precipitation. We found that the drought was associated with consistent reductions in species richness and cover, especially for annual forbs and exotic annual grasses, but not with changes in functional or phylogenetic diversity. Except for total cover and cover of exotic annual grasses, most drought effects did not exceed quantitative expectations based on the four pre-drought studies. Qualitatively, plant community responses to the drought were most concordant with responses to pre-drought interannual rainfall variability in the 15-yr monitoring study, and least concordant with responses to the



geographic gradient in precipitation. Our results suggest that, at least in the short term, extreme drought may cause only a subset of community metrics to respond in ways that exceed normal background variability.

Upward shifts in recruitment of high-elevation tree species in northern Sierra Nevada, California. Wright DH, Nguyen CV, and Anderson S (2016). *California Fish and Game*, **102**: 17-31.

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Description: We compared presence or absence of tree species recruitment in 381 recent random plots in the northern Sierra Nevada of California with 2160 Vegetation Type Map project plots of the 1930s. Of 12 tree species with adequate sample sizes for analysis, we found a significant upward elevation shift in recruitment in three species over this 80-year interval: red fir, western white pine, and mountain hemlock. A marginally significant upward shift was seen in lodgepole pine. All four species are higher elevation conifers in our study area. A few significant latitudinal shifts were also observed, but in a direction counter to the expectation of poleward shift. We believe this reversal is because more northerly latitudes in our study area have lower maximum elevations, whereas the more southerly latitudes have high mountains. One especially high-elevation species, mountain hemlock, became rare to lacking in the northern parts of our region, where the elevations at which it was formerly found may no longer be cool enough for the species. Because our measure of recruitment integrates over multiple years of seed germination and seedling and sapling survival, we believe these changes in small trees may reflect ongoing climatic changes in the Sierra Nevada, foreshadowing changes in plant communities and wildlife habitats.

Hydrologic refugia, plants, and climate change. McLaughlin BC, Ackerly DD, Klos PZ, Natali J, Dawson TE, and Thompson SE (2017). *Global Change Biology*, **23**(8): 2941-1961. <http://dx.doi.org/10.1111/gcb.13629>

Geographic Location: California

Type of Reference: Review Article

Abstract: Climate, physical landscapes, and biota interact to generate heterogeneous hydrologic conditions in space and over time, which are reflected in spatial patterns of species distributions. As these species distributions respond to rapid climate change, microrefugia may support local species persistence in the face of deteriorating climatic suitability. Recent focus on temperature as a determinant of microrefugia insufficiently accounts for the importance of hydrologic processes and changing water availability with changing climate. Where water scarcity is a major limitation now or under future climates, *hydrologic microrefugia* are likely to prove essential for species persistence,



particularly for sessile species and plants. Zones of high relative water availability – mesic microenvironments – are generated by a wide array of hydrologic processes, and may be loosely coupled to climatic processes and therefore buffered from climate change. Here, we review the mechanisms that generate mesic microenvironments and their likely robustness in the face of climate change. We argue that mesic microenvironments will act as species-specific refugia only if the nature and space/time variability in water availability are compatible with the ecological requirements of a target species. We illustrate this argument with case studies drawn from California oak woodland ecosystems. We posit that identification of hydrologic refugia could form a cornerstone of climate-cognizant conservation strategies, but that this would require improved understanding of climate change effects on key hydrologic processes, including frequently cryptic processes such as groundwater flow.

Long-term climate and competition explain forest mortality patterns under extreme drought. Young DJN, Stevens JT, Earles JM, Moore J, Ellis A, Jirk AL, and Latimer AM (2017). *Ecology Letters*, **20**(1): 78-86. <http://dx.doi.org/10.1111/ele.12711>

Geographic Location: California

Type of Reference: Research Paper

Abstract: Rising temperatures are amplifying drought-induced stress and mortality in forests globally. It remains uncertain, however, whether tree mortality across drought-stricken landscapes will be concentrated in particular climatic and competitive environments. We investigated the effects of long-term average climate [i.e. 35-year mean annual climatic water deficit (CWD)] and competition (i.e. tree basal area) on tree mortality patterns, using extensive aerial mortality surveys conducted throughout the forests of California during a 4-year statewide extreme drought lasting from 2012 to 2015. During this period, tree mortality increased by an order of magnitude, typically from tens to hundreds of dead trees per square kilometer (km²), rising dramatically during the fourth year of drought. Mortality rates increased independently with average CWD and with basal area, and they increased disproportionately in areas that were both dry and dense. These results can assist forest managers and policy-makers in identifying the most drought-vulnerable forests across broad geographic areas.

Erosion of refugia in the Sierra Nevada meadows network with climate change.

Maher SP, Morelli TL, Hershey M, Flint AL, Flint LE, et al. (2017). *Ecosphere*, **8**(4): e01673. <http://dx.doi.org/10.1002/ecs2.1673>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Abstract: Climate refugia management has been proposed as a climate adaptation strategy in the face of global change. Key to this strategy is identification of these areas



as well as an understanding of how they are connected on the landscape. Focusing on meadows of the Sierra Nevada in California, we examined multiple factors affecting connectivity using circuit theory, and determined how patches have been and are expected to be affected by climate change. Connectivity surfaces varied depending upon the underlying hypothesis, although meadow area and elevation were important features for higher connectivity. Climate refugia that would promote population persistence were identified from downscaled climate layers, based on locations with minimal climatic change from historical conditions. This approach was agnostic to specific species, yielding a broad perspective about changes and localized habitats. Connectivity was not a consistent predictor of refugial status in the 20th century, but expected future climate refugia tended to have higher connectivity than those that recently deviated from historical conditions. Climate change is projected to reduce the number of refugial meadows on a variety of climate axes, resulting in a sparser network of potential refugia across elevations. Our approach provides a straightforward method that can be used as a tool to prioritize places for climate adaptation.

Wildfires

Changes in temperature and precipitation influence the availability of fuel, and hence the risk of wildfires. Warmer spring and summer temperatures, reduced snowpack and earlier spring snowmelt, and changes in wind patterns have been identified as factors that have caused the increase in wildfires in California. Fires have caused concern in recent years due to their severity and expanse of affected areas. Wildfires lead to changes in forest composition and density, thus affecting carbon sequestration. Scientists are developing models to predict future occurrence of wildfires to assist emergency planners and others in developing wildfire strategies at the local, regional and national levels.

County-level analysis of the impact of temperature and population increases on California wildfire data.

Baltar M, Keeley JE, and Schoenberg FP (2013). *Environmetrics*, 25: 397-405. <http://dx.doi.org/10.1002/env.2257>

Geographic Location: Southern California

Type of Reference: Research Paper

Abstract: The extent to which the apparent increase in wildfire incidence and burn area in California from 1990 to 2006 is affected by population and temperature increases is examined. Using generalized linear models with random effects, we focus on the estimated impacts of increases in mean daily temperatures and populations in different counties on wildfire in those counties, after essentially controlling for the overall differences between counties in their overall mean temperatures and populations. We find that temperature increase appears to have a significant positive impact on both total burn area and number of observed wildfires. Population growth appears to have a much less pronounced impact on total burn area than do annual temperature increases, and



population growth appears to be negatively correlated with the total number of observed wildfires. These effects are especially pronounced in the winter season and in Southern California counties.

Modeling very large-fire occurrences over the continental United States from weather and climate forcing. Barbero R, Abatzoglou JT, Steel EA, and Larkin NK (2014). *Environmental Research Letters*, **9**: 124009. <http://dx.doi.org/10.1088/1748-9326/9/12/124009>

Geographic Location: United States
Type of Reference: Research Paper

Abstract: Very large-fires (VLFs) have widespread impacts on ecosystems, air quality, fire suppression resources, and in many regions account for a majority of total area burned. Empirical generalized linear models of the largest fires (>5000 hectares) across the contiguous United States (US) were developed at ~60 kilometers spatial and weekly temporal resolutions using solely atmospheric predictors. Climate–fire relationships on interannual timescales were evident, with wetter conditions than normal in the previous growing season enhancing VLFs probability in rangeland systems and with concurrent long-term drought enhancing VLFs probability in forested systems. Information at sub-seasonal timescales further refined these relationships, with short-term fire weather being a significant predictor in rangelands and fire danger indices linked to dead fuel moisture being a significant predictor in forested lands. Models demonstrated agreement in capturing the observed spatial and temporal variability including the interannual variability of VLF occurrences within most ecoregions. Furthermore the model captured the observed increase in VLF occurrences across parts of the southwestern and southeastern US from 1984 to 2010 suggesting that, irrespective of changes in fuels and land management, climatic factors have become more favorable for VLF occurrence over the past three decades in some regions. Our modeling framework provides a basis for simulations of future VLF occurrences from climate projections.

Large wildfire trends in the western United States, 1984-2011. Dennison PE, Brewer SC, Arnold JD, and Moritz MA (2014). *Geophysical Research Letters*, **41**: 2928-2933. <http://dx.doi.org/10.1002/2014GL059576>

Geographic Location: Western United States
Type of Reference: Research Paper

Abstract: We used a database capturing large wildfires (> 405 hectares) in the western U.S. to document regional trends in fire occurrence, total fire area, fire size, and day of year of ignition for 1984–2011. Over the western U.S. and in a majority of ecoregions, we found significant, increasing trends in the number of large fires and/or total large fire



area per year. Trends were most significant for southern and mountain ecoregions, coinciding with trends toward increased drought severity. For all ecoregions combined, the number of large fires increased at a rate of seven fires per year, while total fire area increased at a rate of 355 square kilometers (km²) per year. Continuing changes in climate, invasive species, and consequences of past fire management, added to the impacts of larger, more frequent fires, will drive further disruptions to fire regimes of the western U.S. and other fire-prone regions of the world.

Briefing: Climate and Wildfire in Western U.S. Forests. Westerling AL, Brown T, Schoennagel T, Swetnam T, Turner M, and Veblen T (2014). USDA Forest Service RMRS-P-71. http://spot.colorado.edu/~schoenna/images/Westerling_2014_RMRS-P71_Briefing_Climate.pdf

Geographic Location: Western United States

Type of Reference: Report

Abstract: Wildfire in western U.S. federally managed forests has increased substantially in recent decades, with large (>1000 acre) fires in the decade through 2012 over five times as frequent (450 percent increase) and burned area over ten times as great (930 percent increase) as the 1970s and early 1980s. These changes are closely linked to increased temperatures and a greater frequency and intensity of drought. Projected additional future warming implies that wildfire activity may continue to increase in western forests. However, the interaction of changes in climate, fire and other disturbances, vegetation and land management may eventually transform some forest ecosystems and fire regimes, with changes in the spatial extent of forest and fire regime types. In particular, forests characterized by infrequent, high-severity stand replacing fire may be highly sensitive to warming. Increased wildfire combined with warming may transform these ecosystems such that fuel availability, rather than flammability, becomes the dominant constraint on fire activity. Climate will continue to warm for some time regardless of future greenhouse gas emissions, requiring adaptation to warmer temperatures. Changes in forest location, extent and type will result in substantial changes in ecosystem services.

Correlations between components of the water balance and burned area reveal new insights for predicting forest fire area in the southwest United States.

Williams AP, Seager R, Macalady AK, Berkelhammer M, Crimmins MA, et al. (2014). *International Journal of Wildland Fire*, **24**(1): 14-26. <http://dx.doi.org/10.1071/WF14023>.

Geographic Location: Southwest United States

Type of Reference: Research Paper

Abstract: We related measurements of annual burned area in the southwest United States during 1984-2013 to records of climate variability. Within forests, annual burned



area correlated at least as strongly with spring-summer vapor pressure deficit (VPD) as with 14 other drought-related metrics, including more complex metrics that explicitly represent fuel moisture. Particularly strong correlations with VPD arise partly because this term dictates the atmospheric moisture demand. Additionally, VPD responds to moisture supply, which is difficult to measure and model regionally due to complex micrometeorology, land cover and terrain. Thus, VPD appears to be a simple and holistic indicator of regional water balance. Coupled with the well-known positive influence of prior-year cold season precipitation on fuel availability and connectivity, VPD may be utilized for burned area forecasts and also to infer future trends, though these are subject to other complicating factors such as land cover change and management. Assuming an aggressive greenhouse gas emissions scenario, climate models predict mean spring-summer VPD will exceed the highest recorded values in the southwest in nearly 40% of years by the middle of this century. These results forewarn of continued increases in burned forest area in the southwest United States, and likely elsewhere, when fuels are not limiting.

Climate contributors to forest mosaics: Ecological persistence following wildfire.

Kolden C, Abatzoglou JT, Lutz JA, Cansler CA, Kane JT, et al. (2015). *Northwest Science*, **89**(3): 219-238. <http://dx.doi.org/10.3955/046.089.0305>

Geographic Location: Western United States

Type of Reference: Research Paper

Abstract: It is hypothesized that climate impacts forest mosaics through dynamic ecological processes such as wildfires. However, climate-fire research has primarily focused on understanding drivers of fire frequency and area burned, largely due to scale mismatches and limited data availability. Recent datasets, however, allow for the investigation of climate influences on ecological patch metrics across broad regions independent of area burned and at finer scale. One area of particular interest is the distribution of fire refugia within wildfire perimeters. Although much recent research emphasis has been placed on high-severity patches within wildfires, unburned and low-severity patches provide critical remnant habitat and serve as seed sources to initiate colonization and succession in recently burned landscapes. These patches of persistence also may yield insights into approaches for developing fire-resilient landscapes by forest managers and communities seeking to reduce wildfire hazard. Here, we present results showing no decline in proportion of persistent patches in three study areas surrounding National Parks in the western United States, even as research and anecdotal information suggests that fires have become larger and more severe. We also show climate linkages to metrics of persistence that echo previous findings in climate-fire research, and we introduce a framework for addressing global change impacts on forest pattern more broadly. Specifically, we discuss the interactions of multiple drivers at landscape scales and the need to disaggregate relative influences using mixed methods that can address both social and ecological phenomenon.



Increasing elevation of fire in the Sierra Nevada and implications for forest change. Schwartz MW, Butt N, Dolanc CR, Holguin A, Moritz MA, et al. (2015). *Ecosphere*, 6(7): 1-10. <http://dx.doi.org/10.1890/ES15-00003.1>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Abstract: Fire in high-elevation forest ecosystems can have severe impacts on forest structure, function and biodiversity. Using a 105-year data set, we found increasing elevation extent of fires in the Sierra Nevada, and pose five hypotheses to explain this pattern. Beyond the recognized pattern of increasing fire frequency in the Sierra Nevada since the late 20th century, we find that the upper elevation extent of those fires has also been increasing. Factors such as fire season climate and fuel build up are recognized potential drivers of changes in fire regimes. Patterns of warming climate and increasing stand density are consistent with both the direction and magnitude of increasing elevation of wildfire. Reduction in high elevation wildfire suppression and increasing ignition frequencies may also contribute to the observed pattern. Historical biases in fire reporting are recognized, but not likely to explain the observed patterns. The four plausible mechanistic hypotheses (changes in fire management, climate, fuels, ignitions) are not mutually exclusive, and likely have synergistic interactions that may explain the observed changes. Irrespective of mechanism, the observed pattern of increasing occurrence of fire in these subalpine forests may have significant impacts on their resilience to changing climatic conditions.

Different fire-climate relationships on forested and non-forested landscapes in the Sierra Nevada ecoregion. Keeley JE and Syphard AD (2015). *International Journal of Wildland Fire*, 24(1): 27-36. <http://dx.doi.org/10.1071/WF14102>

Geographic Location: Sierra Nevada, California

Type of Reference: Research Paper

Abstract: In the California Sierra Nevada region, increased fire activity over the last 50 years has only occurred in the higher-elevation forests on US Forest Service (USFS) lands, and is not characteristic of the lower-elevation grasslands, woodlands and shrublands on state responsibility lands (Cal Fire). Increased fire activity on USFS lands was correlated with warmer and drier springs. Although this is consistent with recent global warming, we found an equally strong relationship between fire activity and climate in the first half of the 20th century. At lower elevations, warmer and drier conditions were not strongly tied to fire activity over the last 90 years, although prior-year precipitation was significant. It is hypothesized that the fire–climate relationship in forests is determined by climatic effects on spring and summer fuel moisture, with hotter and drier springs leading to a longer fire season and more extensive burning. In contrast, future fire activity in the foothills may be more dependent on rainfall patterns and their effect on the herbaceous fuel load. We predict spring and summer warming will have a significant impact on future fire regimes, primarily in higher-elevation forests.



Lower elevation ecosystems are likely to be affected as much by global changes that directly involve land-use patterns as by climate change.

Climate-induced variations in global wildfire danger from 1979 to 2013. Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, et al. (2015). *Nature Communications*, **6**: 7537. <http://dx.doi.org/10.1038%2Fncoms8537>

Geographic Location: Global

Type of Reference: Research Paper

Abstract: Climate strongly influences global wildfire activity, and recent wildfire surges may signal fire weather-induced pyrogeographic shifts. Here we use three daily global climate data sets and three fire danger indices to develop a simple annual metric of fire weather season length, and map spatio-temporal trends from 1979 to 2013. We show that fire weather seasons have lengthened across 29.6 million square kilometers (km²) (25.3%) of the Earth's vegetated surface, resulting in an 18.7% increase in global mean fire weather season length. We also show a doubling (108.1% increase) of global burnable area affected by long fire weather seasons (41.0 σ above the historical mean) and an increased global frequency of long fire weather seasons across 62.4 million km² (53.4%) during the second half of the study period. If these fire weather changes are coupled with ignition sources and available fuel, they could markedly impact global ecosystems, societies, economies and climate.

Identification of two distinct fire regimes in Southern California: implications for economic impact and future change. Jin Y, Goulden ML, Faivre N, Veraverbeke S, Sun F, et al. (2015). *Environmental Research Letters*, **10**: 094005. <http://dx.doi.org/10.1088/1748-9326/10/9/094005>

Geographic Location: Southern California

Type of Reference: Research Paper

Abstract: The area burned by Southern California wildfires has increased in recent decades, with implications for human health, infrastructure, and ecosystem management. Meteorology and fuel structure are universally recognized controllers of wildfire, but their relative importance, and hence the efficacy of abatement and suppression efforts, remains controversial. Southern California's wildfires can be partitioned by meteorology: fires typically occur either during Santa Ana winds (SA fires) in October through April, or warm and dry periods in June through September (non-SA fires). Previous work has not quantitatively distinguished between these fire regimes when assessing economic impacts or climate change influence. Here we separate five decades of fire perimeters into those coinciding with and without SA winds. The two fire types contributed almost equally to burned area, yet SA fires were responsible for 80% of cumulative 1990–2009 economic losses (\$3.1 Billion). The damage disparity was



driven by fire characteristics: SA fires spread three times faster, occurred closer to urban areas, and burned into areas with greater housing values. Non-SA fires were comparatively more sensitive to age-dependent fuels, often occurred in higher elevation forests, lasted for extended periods, and accounted for 70% of total suppression costs. An improved distinction of fire type has implications for future projections and management. The area burned in non-SA fires is projected to increase 77% ($\pm 43\%$) by the mid-21st century with warmer and drier summers, and the SA area burned is projected to increase 64% ($\pm 76\%$), underscoring the need to evaluate the allocation and effectiveness of suppression investments.

Area burned in the western United States is unaffected by recent mountain pine beetle outbreaks. Hart SJ, Schoennagel T, Veblen TT, and Chapman TB (2015). *Proceedings of the National Academy of Sciences*, **112**(14): 4375-4380. <http://dx.doi.org/10.1073/pnas.1424037112>

Geographic Location: Western United States
Type of Reference: Research Paper

Abstract: In the western United States, mountain pine beetles (MPBs) have killed pine trees across 71,000 square kilometers (km²) of forest since the mid-1990s, leading to widespread concern that abundant dead fuels may increase area burned and exacerbate fire behavior. Although stand-level fire behavior models suggest that bark beetle-induced tree mortality increases flammability of stands by changing canopy and forest floor fuels, the actual effect of an MPB outbreak on subsequent wildfire activity remains widely debated. To address this knowledge gap, we superimposed areas burned on areas infested by MPBs for the three peak years of wildfire activity since 2002 across the western United States. Here, we show that the observed effect of MPB infestation on the area burned in years of extreme fire appears negligible at broad spatial extents. Contrary to the expectation of increased wildfire activity in recently infested red-stage stands, we found no difference between observed area and expected area burned in red-stage or subsequent gray-stage stands during three peak years of wildfire activity, which account for 46% of area burned during the 2002–2013 period. Although MPB infestation and fire activity both independently increased in conjunction with recent warming, our results demonstrate that the annual area burned in the western United States has not increased in direct response to bark beetle activity. Therefore, policy discussions should focus on societal adaptation to the effects of recent increases in wildfire activity related to increased drought severity.



Impact of anthropogenic climate change on wildfire across western US forests.

Abatzoglou JT and Williams AP (2016). *Proceedings of the National Academy of Sciences*, **113**(42): 11770-11775. <http://dx.doi.org/10.1073/pnas.1607171113>

Geographic Location: Western United States

Type of Reference: Research Paper

Abstract: Increased forest fire activity across the western continental United States (US) in recent decades has likely been enabled by a number of factors, including the legacy of fire suppression and human settlement, natural climate variability, and human-caused climate change. We use modeled climate projections to estimate the contribution of anthropogenic climate change to observed increases in eight fuel aridity metrics and forest fire area across the western United States. Anthropogenic increases in temperature and vapor pressure deficit significantly enhanced fuel aridity across western US forests over the past several decades and, during 2000–2015, contributed to 75% more forested area experiencing high ($>1\sigma$) fire-season fuel aridity and an average of nine additional days per year of high fire potential. Anthropogenic climate change accounted for ~55% of observed increases in fuel aridity from 1979 to 2015 across western US forests, highlighting both anthropogenic climate change and natural climate variability as important contributors to increased wildfire potential in recent decades. We estimate that human-caused climate change contributed to an additional 4.2 million ha of forest fire area during 1984–2015, nearly doubling the forest fire area expected in its absence. Natural climate variability will continue to alternate between modulating and compounding anthropogenic increases in fuel aridity, but anthropogenic climate change has emerged as a driver of increased forest fire activity and should continue to do so while fuels are not limiting.

Climate change and future fire regimes: Examples from California. Keeley JE and Syphard AD (2016). *Geosciences*, **6**(3): 37.

<http://dx.doi.org/10.3390/geosciences6030037>

Geographic Location: California

Type of Reference: Review Article

Abstract: Climate and weather have long been noted as playing key roles in wildfire activity, and global warming is expected to exacerbate fire impacts on natural and urban ecosystems. Predicting future fire regimes requires an understanding of how temperature and precipitation interact to control fire activity. Inevitably this requires historical analyses that relate annual burning to climate variation. Fuel structure plays a critical role in determining which climatic parameters are most influential on fire activity, and here, by focusing on the diversity of ecosystems in California, we illustrate some principles that need to be recognized in predicting future fire regimes. Spatial scale of analysis is important in that large heterogeneous landscapes may not fully capture accurate relationships between climate and fires. Within climatically homogeneous subregions, montane forested landscapes show strong relationships between annual



fluctuations in temperature and precipitation with area burned; however, this is strongly seasonal dependent; e.g., winter temperatures have very little or no effect but spring and summer temperatures are critical. Climate models that predict future seasonal temperature changes are needed to improve fire regime projections. Climate does not appear to be a major determinant of fire activity on all landscapes. Lower elevations and lower latitudes show little or no increase in fire activity with hotter and drier conditions. On these landscapes climate is not usually limiting to fires but these vegetation types are ignition-limited. Moreover, because they are closely juxtaposed with human habitations, fire regimes are more strongly controlled by other direct anthropogenic impacts. Predicting future fire regimes is not rocket science; it is far more complicated than that. Climate change is not relevant to some landscapes, but where climate is relevant, the relationship will change due to direct climate effects on vegetation trajectories, as well as by feedback processes of fire effects on vegetation distribution, plus policy changes in how we manage ecosystems.

Controls on interannual variability in lightning-caused fire activity in the western US. Abatzoglou JT, Kolden CA, Balch JK, and Bradley BA (2016).

Environmental Research Letters, **11**(4): 45005. <http://dx.doi.org/10.1088/1748-9326/11/4/045005>

Geographic Location: Western United States

Type of Reference: Research Paper

Abstract: Lightning-caused wildfires account for a majority of burned area across the western United States (US), yet lightning remains among the more unpredictable spatiotemporal aspects of the fire environment and a challenge for both modeling and managing fire activity. A data synthesis of cloud-to-ground lightning strikes, climate and fire data across the western US from 1992 to 2013 was conducted to better understand geographic variability in lightning-caused wildfire and the factors that influence interannual variability in lightning-caused wildfire at regional scales. Distinct geographic variability occurred in the proportion of fires and area burned attributed to lightning, with a majority of fires in the interior western US attributed to lightning. Lightning ignition efficiency was highest across the western portion of the region due to the concomitance of peak lightning frequency and annual nadir in fuel moisture in mid-to-late summer. For most regions the number of total and dry lightning strikes exhibited strong interannual correlation with the number of lightning-caused fires, yet were a poor predictor of area burned at regional scales. Commonality in climate-fire relationships for regional annual area burned by lightning- versus human-ignited fires suggests climate conditions, rather than lightning activity, are the predominant control of interannual variability in area burned by lightning-caused fire across much of the western US.



Recent advances and remaining uncertainties in resolving past and future climate effects on global fire activity. Williams AP and Abatzoglou JT (2016). *Current Climate Change Reports*, 2(1): 1-14. <http://dx.doi.org/10.1007/s40641-016-0031-0>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Fire is an integral component of the Earth system that will critically affect how terrestrial carbon budgets and living systems respond to climate change. Paleo and observational records document robust positive relationships between fire activity and aridity in many parts of the world on interannual to millennial timescales. Observed increases in fire activity and aridity in many areas over the past several decades motivate curiosity as to the degree to which anthropogenic climate change will alter global fire regimes and subsequently Earth's terrestrial biosphere. Importantly, fire responses to warming are not ubiquitous and effects by humans, fuels, and non-temperature climate variables are also apparent in both paleo and observational datasets. The complicated and interactive relationships among these variables necessitate quantitative modeling to better understand future fire responses to global change. Macro-scale fire models exhibit a wide spectrum of complexity. Correlation-based models are inherently superior at representing the current global mean distribution of fire activity but future projections developed from these models cannot account for important processes such as carbon dioxide fertilization and vegetation response after extreme events. Process-based models address some of these limitations by explicitly modeling vegetation dynamics, but this requires false assumptions about processes that are not yet well understood. Continued empirical evaluation of interactions between fire, vegetation, climate, and humans, and resultant improvements to both correlation- and process-based macro-fire models, are mandatory to better understand the past and future of the Earth system.

Quantifying the human influence on fire ignition across the western US. Fusco EJ, Abatzoglou JT, Balch JK, Finn JT, and Bradley BA (2016). *Ecological Applications*, 26(8): 2390-2401. <http://dx.doi.org/10.1002/eap.1395>

Geographic Location: Western United States

Type of Reference: Research Paper

Abstract: Humans have a profound effect on fire regimes by increasing the frequency of ignitions. Although ignition is an integral component of understanding and predicting fire, to date fire models have not been able to isolate the ignition location, leading to inconsistent use of anthropogenic ignition proxies. Here, we identified fire ignitions from the Moderate Resolution Imaging Spectrometer (MODIS) burned area product (2000-2012) to create the first remotely sensed, consistently derived, and regionally comprehensive fire ignition data set for the western United States. We quantified the spatial relationships between several anthropogenic land use/disturbance features and ignition for ecoregions within the study area, and used hierarchical partitioning to test



how the anthropogenic predictors of fire ignition vary among ecoregions. The degree to which anthropogenic features predicted ignition varied considerably by ecoregion, with the strongest relationships found in the Marine West Coast Forest and North American Desert ecoregions. Similarly, the contribution of individual anthropogenic predictors varied greatly among ecoregions. Railroad corridors and agricultural presence tended to be the most important predictors of anthropogenic ignition while population density and roads were generally poor predictors. Although human population has often been used as a proxy for ignitions at global scales, it is less important at regional scales when more specific land uses (e.g., agriculture) can be identified. The variability of ignition predictors among ecoregions suggests that human activities have heterogeneous impacts in altering fire regimes within different vegetation types and geographies.

Increasing western US forest wildfire activity: Sensitivity to changes in the timing of spring. Westerling AL (2016). *Philosophical Transactions of the Royal Society B*, **371**(1696): 20150178. <http://dx.doi.org/10.1098/rstb.2015.0178>

Geographic Location: Western United States

Type of Reference: Research Paper

Abstract: Prior work shows western US forest wildfire activity increased abruptly in the mid-1980s. Large forest wildfires and areas burned in them have continued to increase over recent decades, with most of the increase in lightning-ignited fires. Northern US Rockies forests dominated early increases in wildfire activity, and still contributed 50% of the increase in large fires over the last decade. However, the percentage growth in wildfire activity in Pacific northwestern and southwestern US forests has rapidly increased over the last two decades. Wildfire numbers and burned area are also increasing in non-forest vegetation types. Wildfire activity appears strongly associated with warming and earlier spring snowmelt. Analysis of the drivers of forest wildfire sensitivity to changes in the timing of spring demonstrates that forests at elevations where the historical mean snow-free season ranged between two and four months, with relatively high cumulative warm-season actual evapotranspiration, have been most affected. Increases in large wildfires associated with earlier spring snowmelt scale exponentially with changes in moisture deficit, and moisture deficit changes can explain most of the spatial variability in forest wildfire regime response to the timing of spring.

Greater temperature and precipitation extremes intensify western U.S. droughts, wildfire severity, and Sierra Nevada tree mortality. Crockett JL and Westerling AL (2017). *Journal of Climate*, **31**(1): 341-354. <http://dx.doi.org/10.1175/JCLI-D-17-0254.1>

Geographic Location: Western United States

Type of Reference: Research Paper



Abstract: Extensive drought in the western United States (WUS) during the twenty-first century and associated wildfire and tree mortality incidence has highlighted the potential for greater area of severity within widespread droughts. To place recent WUS droughts into a historical context, the authors analyzed gridded daily climate (temperature, precipitation, and climatic water deficit) data to identify and characterize the spatiotemporal evolution of the largest WUS droughts of the last 100 years, with an emphasis on severe cores within drought extents. Cores of droughts during the last 15 years (2000–02 and 2012–14) covered a greater area than in earlier droughts, driven by greater temperature and precipitation extremes. Comparing fire extent and severity before, during, and after drought events using the monitoring trends in burn severity dataset (1984–2014), the authors found fire size and high-severity burn extent were greater during droughts than before or after. Similarly, recent Sierra Nevada forest mortality was greatest in cores immediately after the drought. Climate simulations anticipate greater extremes in temperature and precipitation in a warming world; droughts and related impacts of the last 15 years may presage the effects of these extremes.

Drought, tree mortality, and wildfire in forests adapted to frequent fire.

Stephens SL, Collins BM, Fettig CJ, Finney MA, Hoffman CM, et al. (2018). *Bioscience*, 68(2): 77-88. <http://dx.doi.org/10.1093/biosci/bix146>

Geographic Location: California

Type of Reference: Review Article

Abstract: Massive tree mortality has occurred rapidly in frequent-fire-adapted forests of the Sierra Nevada, California. This mortality is a product of acute drought compounded by the long-established removal of a key ecosystem process: frequent, low- to moderate-intensity fire. The recent tree mortality has many implications for the future of these forests and the ecological goods and services they provide to society. Future wildfire hazard following this mortality can be generally characterized by decreased crown fire potential and increased surface fire intensity in the short to intermediate term. The scale of present tree mortality is so large that greater potential for “mass fire” exists in the coming decades, driven by the amount and continuity of dry, combustible, large woody material that could produce large, severe fires. For long-term adaptation to climate change, we highlight the importance of moving beyond triage of dead and dying trees to making “green” (live) forests more resilient.



Aquatic Vegetation

Extreme warming challenges sentinel status of kelp forests as indicators of climate change. Reed D, Washburn L, Rassweiler A, Miller R, Bell T, and Harrer S (2016). *Nature Communications*, **7**: 13757. <http://dx.doi.org/10.1038/ncomms13757>

Geographic Location: Santa Barbara Channel, California

Type of Reference: Research Paper

Abstract: The desire to use sentinel species as early warning indicators of impending climate change effects on entire ecosystems is attractive, but we need to verify that such approaches have sound biological foundations. A recent large-scale warming event in the North Pacific Ocean of unprecedented magnitude and duration allowed us to evaluate the sentinel status of giant kelp, a coastal foundation species that thrives in cold, nutrient-rich waters and is considered sensitive to warming. Here, we show that giant kelp and the majority of species that associate with it did not presage ecosystem effects of extreme warming off southern California despite giant kelp's expected vulnerability. Our results challenge the general perception that kelp-dominated systems are highly vulnerable to extreme warming events and expose the more general risk of relying on supposed sentinel species that are assumed to be very sensitive to climate change.

Harmful algal blooms

Harmful algal blooms are colonies of algae and/or plant-like bacteria (cyanobacteria) that grow out of control, threatening fisheries, marine and freshwater ecosystems, public health and economies. Harmful algal blooms can produce natural toxins that contaminate seafood and waterbodies used for recreation or drinking water sources. Even without producing toxins, harmful algal blooms can damage aquatic environments by suffocating fish, blocking sunlight, or depleting oxygen in the water. Scientific data indicates that harmful algal blooms are expanding globally in distribution, frequency and abundance. Scientists hypothesize that climate change is a driving influence in harmful algal bloom expansion due to increased temperatures, nutrients and carbon dioxide levels in water, and decreased water mixing.

Harmful algal blooms and climate change: Learning from the past and present to forecast the future. Wells ML, Trainer VL, Smayda TJ, Karlson BSO, Trick CG, et al. (2015). *Harmful Algae*, **49**: 68-69. <http://dx.doi.org/10.1016/j.hal.2015.07.009>

Geographic Location: Global

Type of Reference: Review Article

Abstract: Climate change pressures will influence marine planktonic systems globally, and it is conceivable that harmful algal blooms may increase in frequency and severity. These pressures will be manifest as alterations in temperature, stratification, light,



ocean acidification, precipitation-induced nutrient inputs, and grazing, but absence of fundamental knowledge of the mechanisms driving harmful algal blooms frustrates most hope of forecasting their future prevalence. Summarized here is the consensus of a recent workshop held to address what currently is known and not known about the environmental conditions that favor initiation and maintenance of harmful algal blooms. There is expectation that harmful algal bloom (HAB) geographical domains should expand in some cases, as will seasonal windows of opportunity for harmful algal blooms at higher latitudes. Nonetheless there is only basic information to speculate upon which regions or habitats HAB species may be the most resilient or susceptible. Moreover, current research strategies are not well suited to inform these fundamental linkages. There is a critical absence of tenable hypotheses for how climate pressures mechanistically affect HAB species, and the lack of uniform experimental protocols limits the quantitative cross-investigation comparisons essential to advancement. A HAB “best practices” manual would help foster more uniform research strategies and protocols, and selection of a small target list of model HAB species or isolates for study would greatly promote the accumulation of knowledge. Despite the need to focus on keystone species, more studies need to address strain variability within species, their responses under multifactorial conditions, and the retrospective analyses of long-term plankton and cyst core data; research topics that are departures from the norm. Examples of some fundamental unknowns include how larger and more frequent extreme weather events may break down natural biogeographic barriers, how stratification may enhance or diminish HAB events, how trace nutrients (metals, vitamins) influence cell toxicity, and how grazing pressures may leverage, or mitigate HAB development. There is an absence of high quality time-series data in most regions currently experiencing HAB outbreaks, and little if any data from regions expected to develop HAB events in the future. A subset of observer sites is recommended to help develop stronger linkages among global, national, and regional climate change and HAB observation programs, providing fundamental datasets for investigating global changes in the prevalence of harmful algal blooms. Forecasting changes in HAB patterns over the next few decades will depend critically upon considering harmful algal blooms within the competitive context of plankton communities, and linking these insights to ecosystem, oceanographic and climate models. From a broader perspective, the nexus of HAB science and the social sciences of harmful algal blooms is inadequate and prevents quantitative assessment of impacts of future HAB changes on human well-being. These and other fundamental changes in HAB research will be necessary if HAB science is to obtain compelling evidence that climate change has caused alterations in HAB distributions, prevalence or character, and to develop the theoretical, experimental, and empirical evidence explaining the mechanisms underpinning these ecological shifts.

An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. McCabe RM, Hickey BM, Kudela RM, Lefebvre KA, Adams NG, Bill BD, et al. (2016). *Geophysical Research Letters*, **43**(19): 10,366-10,376.
<http://dx.doi.org/10.1002/2016GL070023>



Geographical Location: United States West Coast, Pacific Ocean
Type of Reference: Review Article

Abstract: A coastwide bloom of the toxigenic diatom *Pseudo-nitzschia* in spring 2015 resulted in the largest recorded outbreak of the neurotoxin, domoic acid, along the North American west coast. Elevated toxins were measured in numerous stranded marine mammals and resulted in geographically extensive and prolonged closures of razor clam, rockcrab, and Dungeness crab fisheries. We demonstrate that this outbreak was initiated by anomalously warm ocean conditions. *Pseudo-nitzschia australis* thrived north of its typical range in the warm, nutrient-poor water that spanned the northeast Pacific in early 2015. The seasonal transition to upwelling provided the nutrients necessary for a large-scale bloom; a series of spring storms delivered the bloom to the coast. Laboratory and field experiments confirming maximum growth rates with elevated temperatures and enhanced toxin production with nutrient enrichment, together with a retrospective analysis of toxic events, demonstrate the potential for similarly devastating ecological and economic disruptions.

The effects of chlorophyll and water temperature on harmful algal bloom species off the southern coast of California. Griffith R. (2016). *McNair Scholars Research Journal*, 3(5).

Geographic Location: California Southern Coast, Pacific Ocean
Type of Reference: Research Paper

Abstract: Harmful algal blooms are dense aggregates of algae that negatively impact local economies, marine or freshwater ecosystems, and/or public health. Some HABs produce toxins that cause various illnesses that harm both humans and marine wildlife such as Diarrhetic Shellfish Poisoning, Paralytic Shellfish Poisoning and Amnesic Shellfish Poisoning. While it is known that HABs persist when nutrients and water temperature combine to create the optimal environmental conditions for their propagation, there are many questions surrounding exactly what these conditions are and how they are reached. Therefore, the focus of this project as part of the NASA Student Airborne Research Program was to look at the effects of chlorophyll and water temperature on 6 different HAB species along the California Coast from San Diego to Monterey Bay. In this study, it is shown using time series and cluster analysis indicate both positive and negative correlations of water temperature with respect to HAB species, but only positive correlations between chlorophyll and HAB species. Correlations of chlorophyll indicate satellite imagery can be used to map HABs initially but not predict them. Results are consistent with previous attempts to model distribution of HAB species (e.g., *Pseudo-Nitzschia*) in California Coastal waters, as they indicate that a strong regional component is involved in doing so. This demonstrates the need for a more integrative approach to HAB forecasting along the California Coast that takes into account not just temperature and chlorophyll measurements, but also differences in water chemistry and other environmental conditions between sampling stations that



result from differences in coastal topography, river discharge, coastal bathymetry, and meteorological parameters.

The pelagic ecosystem in the Northern California Current off Oregon during the 2014-2016 warm anomalies within the context of the past 20 years. Peterson WT, Fisher JL, Strub PT., Du X, Risien C, et al. (2017). *Journal of Geophysical Research Oceans*, **122**(9): 7267–7290. <http://dx.doi.org/10.1002/2017JC012952>

Geographic Location: Northern California Current, Pacific Ocean

Type of Reference: Research Paper

Abstract: A warm anomaly in the upper ocean, colloquially named “the Blob,” appeared in the Gulf of Alaska during the calm winter of 2013–2014, spread across the northern North Pacific (NP) Ocean, and shifted eastward and onto the Oregon shelf. At least 14 species of copepods occurred which had never been observed in shelf/slope waters off Oregon, some of which are known to have NP Gyre affinities, indicating that the source waters of the coastal “Blob” were likely of both offshore (from the west) and subtropical/tropical origin. The anomalously warm conditions were reduced during strong upwelling in spring 2015 but returned when upwelling weakened in July 2015 and transitioned to downwelling in fall 2015. The extended period of warm conditions resulted in prolonged effects on the ecosystem off central Oregon, lasting at least through 2016. Impacts to the lower trophic levels were unprecedented and include a novel plankton community composition resulting from increased copepod, diatom, and dinoflagellate species richness and increased abundance of dinoflagellates. Additionally, the multiyear warm anomalies were associated with reduced biomass of copepods and euphausiids, high abundance of larvaceans and doliolids (indicators of oligotrophic ocean conditions), and a toxic diatom bloom (*Pseudo-nitzschia*) throughout the California Current in 2015, thereby changing the composition of the food web that is relied upon by many commercially and ecologically important species.

Ocean warming since 1982 has expanded the niche of toxic algal blooms in the North Atlantic and North Pacific oceans. Gobler CJ, Doherty OM, Hattenrath-Lehmann TK, Griffith AW, Kang Y, et al. (2017). *Proceedings of the National Academy of Sciences*, **114**(19): 4975-4980. <http://dx.doi.org/10.1073/pnas.1619575114>

Geographic Location: North Atlantic Ocean and North Pacific Ocean

Type of Reference: Research Paper

Abstract: This study used high-resolution (daily, quarter-degree resolution) sea- surface temperature records to model trends in growth rates and bloom-season duration for two of the most toxic and widespread harmful algal bloom species indigenous to the North Atlantic and North Pacific oceans. *Alexandrium fundyense* synthesizes saxitoxin and *Dinophysis acuminata* synthesizes okadaic acid, which cause



the human health syndromes paralytic and diarrhetic shellfish poisoning, respectively. The model provided hindcasts of harmful algal bloom (HAB) events that were consistent with in situ observations from long-term monitoring programs during the same time period. This study provides evidence that increasing ocean temperatures have already facilitated the intensification of these, and likely other, HABs and thus contribute to an expanding human health threat.

Climatic regulation of the neurotoxin domoic acid. McKibber SM, Peterson W, Wood AM, Trainer VL, Hunter M, and White AE (2017). *Proceedings of the National Academy of Sciences*, **114**(2): 239-244. <http://dx.doi.org/10.1073/pnas.1606798114>

Geographic Location: Northern California Current, Pacific Ocean

Type of Reference: Research Paper

Abstract: Domoic acid is a potent neurotoxin produced by certain marine microalgae that can accumulate in the foodweb, posing a health threat to human seafood consumers and wildlife in coastal regions worldwide. Evidence of climatic regulation of domoic acid in shellfish over the past 20 years in the Northern California Current regime is shown. The timing of elevated domoic acid is strongly related to warm phases of the Pacific Decadal Oscillation and the Oceanic Niño Index, an indicator of El Niño events. Ocean conditions in the northeast Pacific that are associated with warm phases of these indices, including changes in prevailing currents and advection of anomalously warm water masses onto the continental shelf, are hypothesized to contribute to increases in this toxin. We present an applied domoic acid risk assessment model for the US West Coast based on combined climatic and local variables. Evidence of regional-to basin-scale controls on domoic acid has not previously been presented. Our findings have implications in coastal zones worldwide that are affected by this toxin and are particularly relevant given the increased frequency of anomalously warm ocean conditions.

Impacts of the 2014 severe drought on the *Microcystis* bloom in San Francisco Estuary. Lehman PW, Kurobe T, Lesmeister S, Baxa D, Tung A, and Ten SJ (2017). *Harmful Algae*, **63**:94-108. <http://dx.doi.org/10.1016/j.hal.2017.01.011>

Geographic Location: San Francisco Estuary, California

Type of Reference: Research Paper

Abstract: The increased frequency and intensity of drought with climate change may cause an increase in the magnitude and toxicity of freshwater cyanobacteria harmful algal blooms (CHABs), including *Microcystis* blooms, in San Francisco Estuary, California. As the fourth driest year on record in San Francisco Estuary, the 2014 drought provided an opportunity to directly test the impact of severe drought on cyanobacteria blooms in SFE. A field sampling program was conducted between July



and December 2014 to sample a suite of physical, chemical, and biological variables at 10 stations in the freshwater and brackish reaches of the estuary. The 2014 *Microcystis* bloom had the highest biomass and toxin concentration, earliest initiation, and the longest duration, since the blooms began in 1999. Median chlorophyll *a* concentration increased by 9 and 12 times over previous dry and wet years, respectively. Total microcystin concentration also exceeded that in previous dry and wet years by a factor of 11 and 65, respectively. Cell abundance determined by quantitative PCR indicated the bloom contained multiple potentially toxic cyanobacteria species, toxic *Microcystis* and relatively high total cyanobacteria abundance. The bloom was associated with extreme nutrient concentrations, including a 20-year high in soluble reactive phosphorus concentration and low to below detection levels of ammonium. Stable isotope analysis suggested the bloom varied with both inorganic and organic nutrient concentration, and used ammonium as the primary nitrogen source. Water temperature was a primary controlling factor for the bloom and was positively correlated with the increase in both total and toxic *Microcystis* abundance. In addition, the early initiation and persistence of warm water temperature coincided with the increased intensity and duration of the *Microcystis* bloom from the usual 3 to 4 months to 8 months. Long residence time was also a primary factor controlling the magnitude and persistence of the bloom, and was created by a 66% to 85% reduction in both the water inflow and diversion of water for agriculture during the summer. We concluded that severe drought conditions can lead to a significant increase in the abundance of *Microcystis* and other cyanobacteria, as well as their associated toxins.



APPENDIX

Methodology

Publications were identified and selected for inclusion in this bibliography using the following approach.

1. An initial literature search was conducted in Web of Science and SCOPUS using the following search query for publications released during the years 2012 through 2018:

“climate change” AND “California”
“climate change” AND “California” AND “impacts”

2. A separate Google Scholar search was conducted using the names of researchers who had contributed to OEHHA’s climate change indicator reports, to identify any papers with recent monitoring data or research not captured in Web of Science or SCOPUS.
3. Staff routinely monitored environmental newsletters, websites of research institutions and government entities and the popular press. Several scientific papers and reports were identified from these sources.
4. Search results and other identified references were screened to ensure they meet the following criteria:

Credibility of source: References must be published in a peer-reviewed journal or issued as a report by a governmental agency, research institution or any other entity generally recognized as authoritative in the subject.

Geographic coverage: California-specific references were targeted. However, documents reporting climate conditions or impacts in other geographic areas were included if findings are of global significance or are relevant to California.

Topics included: new scientific understanding and observational data describing current or past conditions. References selected describe past or current observational data, or present new or modified scientific understanding about changes in climate; the causes or drivers of climate change; and impacts of climate change on the environment, plants, animals and humans.

Topics excluded: future projections, management options or policy measures, and data solely from controlled experiments. References that primarily present

future scenarios or modelled projections, or that mainly discuss policy, mitigation or adaptation measures were excluded. References that report findings based solely on controlled experimental studies were also excluded.

5. Search results were organized into the following groups. Except for authoritative reports, the four groups are the categories used by OEHHA to organize its climate change indicator reports.
 - *Authoritative reports*
 - *Drivers of climate change*
 - *Changes in climate*
 - *Impacts of climate on physical systems*
 - *Impacts of climate on biological systems*