OFFICE OF ENVIRONMENTAL HEALTH HAZARD ASSESSMENT

Climate Change Indicators

Recent Research on Climate Change:

An annotated bibliography with an emphasis on California

February 2015

Air, Community, and Environmental Research Branch

Office of Environmental Health Hazard Assessment

California Environmental Protection Agency

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APPENDIX A-1

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Commonly Used Acronyms

CH_4	Methane
CO_2	Carbon dioxide
CONUS	Continental United States
ENSO	El Niño-Southern Oscillation
EWL	Energy-water-land
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LULC	Land use and land cover
N_2O	Nitrous oxide
NCA	National Climate Assessment
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OC	Organic carbon
PDO	Pacific Decadal Oscillation
SOC	Soil organic carbon
SST	Sea surface temperature
SWE	Snow water equivalent
SWV	Stratospheric water vapor
USGCRP	U.S. Global Change Research Program

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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 relevant to climate change and its impacts on California. Information from these sources is organized and presented in this annotated bibliography, which is intended as a source of current and emerging scientific information on climate change for environmental and public health agencies, the research community, non-government organizations, and the public. The findings in the references can, in some cases, be used as the basis for a separate effort by OEHHA to compile indicators of climate change in California (*Indicators of Climate Change in California* (OEHHA, 2013)).

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 annotated bibliography covers research published from 2010 to 2013, along with some authoritative reports from 2014 (see next page). This document adds to the literature summarized in an earlier bibliography (OEHHA, 2013), which covered publications from mid-2009 to 2012. Inclusion of publications from overlapping years allows us to capture useful references that were not included in the 2013 report. No references from the 2013 bibliography are repeated in this document. Together, the bibliographies present a comprehensive overview of recent climate change research and findings, particularly those with a focus on California and indicators of climate change in the state.

Identifying and selecting references

This annotated bibliography was compiled following a literature search for publications that describe past and current data, or new or modified scientific understanding about changes in climate, the causes or drivers of climate change, and its impacts. Publications that relate to California were targeted, although references that cover other geographic areas were included if their findings are applicable or relevant to California. Specifically excluded are references that primarily present future scenarios or modelled projections, or that mainly discuss mitigation or adaptation measures. The identification and selection of publications were guided by the considerations further described in the appendix.

Although OEHHA took every effort to be comprehensive in its literature search, relevant papers may have been missed. The absence of references on a given subject should not be interpreted as an indication of its lack of relevance or significance to California.

Structure of the report

References are organized into five categories, four of which are used for the indicators presented in OEHHA's report, *Indicators of Climate Change in California* (OEHHA, 2013). The following define the categories presented in this bibliography:

Authoritative reports
Certain national and international scientific organizations are generally recognized to be authoritative because they are comprised of scientists and other researchers with well-known, established expertise. These organizations, typically affiliated with government entities, publish reports, assessments or periodic updates that focus on a single topic or cover multiple climate change-related topics. Examples include the Intergovernmental Panel on Climate Change (IPCC), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Global Change Research Program (USGCRP).

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) alter the energy balance of the climate system and are drivers of climate change.

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. Changes in climate can be tracked based on observational data for these parameters.

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 erosion, sea level rise, salt water intrusion, and changes in snowmelt runoff. Globally, physical systems are being affected by regional climate change, particularly temperature increases.

Impacts of climate on biological systems
Terrestrial, marine and freshwater biological systems are strongly influenced by climatic conditions. Increasing temperatures can impact humans (e.g., increased mortality during heat waves), vegetation (e.g., wildfires and vegetation distribution shifts) and animals (e.g., small mammal migration).

The summaries

With the exception of authoritative reports, the categories listed above are subcategorized into research areas. Within these subcategories, the references are arranged by publication date, from the earliest to most recent. A full citation is provided

for each paper, along with a summary that discusses background information, the purpose of the study or review, methods used, results, and conclusions. All information contained in the summaries, including findings and conclusions, are taken solely from the reference, and do not represent OEHHA's opinions or findings. Summaries are written for an informed audience (not necessarily having technical expertise in the subject of the paper), and readers are advised to refer to the paper for technical details.

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 (2013). *Indicators of Climate Change in California*. Office of Environmental Health Hazard Assessment, California Environmental Protection Agency.

Authoritative Reports

This chapter presents summaries of publications by authoritative national and international scientific organizations in topics relating to climate and climate change. Although this bibliography focused on papers reporting on California, authoritative reports providing information at the national or global level were summarized if the information included California or was considered relevant to the state.

A description of each authoritative organization is provided below, along with the title(s) of the report(s) for which summaries are included in this bibliography.

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts. Three working groups produced reports, two of which are summarized in this bibliography. The third working group report, *Mitigation of Climate Change,* is beyond the scope of this document.

- *Climate Change 2013: The Physical Science Basis*
- *Climate Change 2014: Impacts, Adaptation, and Vulnerability*
- *Climate Change 2014: Synthesis Report*

The UNEP assesses global, regional and national environmental conditions and trends, and promotes sustainable development of the global environment.

- *Environmental effects of ozone depletion and its interactions with climate change: Progress reports*

The WMO is the United Nations' authoritative voice on the state and behavior of the Earth's atmosphere, its interactions with the oceans, the climate it produces and the distribution of water resources.

- *Climate, carbon and coral reefs*

The National Oceanic and Atmospheric Administration's (NOAA) of the U.S. Department of Commerce is responsible for daily weather forecasts and severe storm warnings as well as climate monitoring for fisheries management and coastal restoration. NOAA is a primary provider of climate science, data, tools and information.

- *Climate Change impacts: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries*
- *Climate Sensitivity of the National Estuarine Research Reserve System*

The U.S. Global Change Research Program (USGCRP) was established to coordinate and integrate federal research on changes in the global environment. Thirteen

departments and agencies participate in the program, which is responsible for National Climate Assessments (NCA) every four years. As part of the process of preparing the third assessment, individuals and teams were invited to submit technical inputs for consideration by the NCA Development Advisory Committee.

- *Technical inputs relating to sectors and sectoral crosscuts, the Southwest Region (which includes California), and indicators for an ongoing national climate assessment process*
- *Climate change impacts in the United States, Third National Climate Assessment*
- *Climate Change and Agriculture in the United States*

The National Academies' National Research Council (NRC) enlists the nation's top scientists, engineers and other experts to provide independent advice to the government on science and technology issues that frequently affect policy decisions.

- *A Review of the Draft 2013 National Climate Assessment*
- *Abrupt Impacts of Climate Change: Anticipating Surprises*

The U.S. Department of Agriculture is a federal agency responsible for national policy on farming, forestry and food. Among its programs are those that assure food safety and protect natural resources.

- *Climate Change and Agriculture in the United States*

The American Meteorological Society (AMS) is a professional organization that promotes the development and dissemination of information on atmospheric and related oceanic and hydrologic sciences.

- *State of the Climate in 2012*
- *Explaining Extreme Events of 2012 from a Climate Perspective*
- *Explaining Extreme Events of 2013 from a Climate Perspective*

Environmental effects of ozone depletion and its interactions with climate change: Progress reports (*for years 2010 and 2011)*. United Nations Environmental Programme, Environmental Effects Assessment Panel.

2010 report. http://ozone.unep.org/Assessment_Panels/EEAP/eeap-report2010.pdf
2011 report.
http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports/TEAP_Progress_Report_May_2011.pdf

The Montreal Protocol on Substances that Deplete the Ozone Layer is an international treaty designed to protect the stratospheric ozone layer by phasing out the production of ozone-depleting substances such as chlorofluorocarbons. Stratospheric ozone absorbs most of the potentially harmful ultraviolet (UV) radiation, shielding it from reaching the surface of the planet. The parties to the Montreal Protocol are informed by the United Nations Environmental Effects Assessment Panel (EEAP). The EEAP deals with two focal issues. The first focus is the effects of increased UV radiation on human health,

animals, plants, biogeochemistry, air quality, and materials. The second focus is on interactions between UV radiation and global climate change and how these may affect humans and the environment.

The EEAP has produced a detailed report every four years since 2006 with the last full report published in 2010. In the years in between, the EEAP produces shorter progress reports, which assess developments in key areas. Highlights of the 2010 and 2011 reports in the journal *Photochemical & Photobiological Sciences* describe how their data, modeling and interpretations are informing parties to the Montreal Protocol, other policymakers and scientists. These reports are summarized below.

2010 Report

This Assessment reports on key findings on environment and health, emphasizing impacts from the interactions between ozone depletion and climate change. Highlighted below are main points discussed:

- There are strong interactions between ozone depletion and changes in climate induced by increasing atmospheric greenhouse gases.
- Health effects associated with combined changes in solar UV radiation and climate are plausible; directed studies are required to guide health care decisions and future policies regarding health care.
- Predicted changes in climate may modify plant and ecosystem responses to UV radiation.
- UV radiation promotes the breakdown of dead plant material and consequently carbon loss to the atmosphere.
- Variations in UV-B radiation caused by climate change and ozone depletion can have large effects on plant interactions with pests, with important implications for food security and food quality.
- Climate change will alter the exposure of aquatic organisms to solar UV radiation by influencing their depth distribution as well as the transparency of the water.
- Enhanced solar UV-B radiation in conjunction with rising global temperatures may negatively affect growth of seaweeds that have ecologic and economic importance.
- Climate-driven changes in environmental conditions may exceed the capacity of protective strategies of aquatic organisms to adapt to solar UV radiation.

2011 report

Highlighted below are key points discussed in this progress report:

- Changes in the climate resulting from depletion of stratospheric ozone and global warming might result in a rise in the incidence and prevalence of water-borne and vector-borne infections.
- There are interactions between the effects of solar UV radiation and climate change on the processes that drive the carbon cycle.

- Projected shifts to warmer and drier conditions, such as in the Mediterranean and in western North America, will increase UV-induced carbon loss to the atmosphere.
- In mid- and high-latitude oceanic areas, the capacity to take up atmospheric carbon dioxide (CO_2) is decreasing.
- Predicted climate-related increases in runoff from the Arctic and alpine regions to aquatic ecosystems will accelerate the UV-induced breakdown of soil organic carbon into atmospheric CO_2.
- Feedbacks involving greenhouse gases other than CO_2 are increasing due to interactive effects of UV radiation and climate change.
- Photochemically produced tropospheric ozone is projected to increase.

Climate, Carbon, and Coral Reefs. World Meteorological Organization (2010). WMO-No. 1063.
http://www.wmo.int/pages/prog/wcp/agm/publications/documents/Climate_Carbon_CoralReefs.pdf

This report, prepared by the World Meteorological Organization and the Convention on Biological Diversity, summarizes the CO_2 threat to coral reefs, the science supporting projections and the solutions that are needed. Coral reefs cover 0.2% of the world's ocean, but contain about 25% of marine species and provide an array of valuable goods and services. Increasing concentrations of CO_2 lead to ocean warming, which can cause extensive coral bleaching events and mortality, and ocean acidification, which impairs the ability of coral reefs to grow and sustain their structure and function. Climate change, ocean acidification, and regional or local disturbances can act together to degrade the resilience of coral reefs. An estimated 19% of the original coral reef area has already been lost, with 15% seriously threatened in the next 10-20 years, and an additional 20% threatened in 20-40 years.

Elevated ocean temperatures, the primary cause of mass coral bleaching events, result in the loss of symbiotic algae, impeding the growth, reproduction, or even survival of coral. The intensity and scale of observed bleaching events have increased since the 1960s; bleaching events in 1998, 2002 and 2005 have affected entire reef systems. Experimental studies indicate ocean acidification—another consequence of atmospheric CO_2 emissions—will shift coral reefs from growing to dissolving structures by the end of the century; concentrations of carbonate ions, required by marine organisms to form shells, decline with ocean acidification. More frequent severe storms will exacerbate these destructive impacts as brittle corals will have greater sensitivity to storm damage. Changes in ocean salinity, ocean circulation trends, and land use practices impact coral reef health. Sea level rise provides corals with greater space to grow upwards, but exposes corals to increased sedimentation due to coastal erosion. Tropical cyclones can benefit coral by alleviating thermal stress, yet storm surges may damage coral structures.

The authors state that immediate action to reduce carbon emissions and atmospheric CO_2 is essential to mitigate the current trajectory of coral reef degradation. Reports to policymakers should promote environmental stewardship and consider the ecological and socioeconomic consequences of reef ecosystem losses. Seasonal forecasts, real-time monitoring, and improved modelling will increase scientific and reef management capacity.

Climate Change impacts: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries. National Oceanic and Atmospheric Administration (2010). Largier J, et al. (Eds.). Report of a Joint Working Group of the Gulf of the Farallones and Cordell Bank National Marine Sanctuaries Advisory Councils. Marine Sanctuaries Conservation Series ONMS-11-04.
http://sanctuaries.noaa.gov/science/conservation/pdfs/gf_cbnms_climate_report.pdf

Developed by a joint working group of the Gulf of the Farallones (GFNMS) and Cordell Bank (CBNMS) National Marine Sanctuary Advisory Councils, this report identifies and synthesizes potential climate change impacts to habitats and biological communities in the waters off north-central California, within which Gulf of the Farallones and Cordell Bank national marine sanctuaries are located. It presents scientific observations and expectations to identify potential issues related to changing climate–with an emphasis on the most likely ecological impacts and the impacts that would be most severe if they occur.

The report addresses the physical effects of climate change; the biological implications of climate change on the study region; observed and projected ecosystem-wide responses specific to different habitats (pelagic, benthic, island, sandy beach, rocky intertidal, nearshore subtidal and estuarine); the implications of multiple stressors (including pollution, invasive species and fishing) acting on an ecosystem and cumulative impacts; and direct impacts on humans. Some of the report's findings are highlighted below.

- Physical impacts associated with climate change include the following:
  - Observed increase in sea level (100 year record at mouth of San Francisco Bay)
  - Expected increase in coastal erosion associated with changes in sea level and storm waves
  - Observed decrease in spring runoff of freshwater through San Francisco Bay (decreased Sierra snowpack)
  - Observed increase in precipitation variability (drier dry years, wetter wet years)
  - Observed increase in surface ocean temperature offshore of the continental shelf (50-year record)
  - Observed increase in winds driving coastal upwelling of nutrient-rich waters and associated observed decrease in surface ocean temperature over the continental shelf (30-year record)
  - Observed increase in extreme weather events (winds, waves, storms)

- Expected decrease in seawater pH, due to uptake of CO_2 by the ocean

- The above physical changes may influence a variety of critical biological processes. Impacts on marine species depend on both the environmental changes and the responses of other species it interacts with. Species can (1) remain in the same area but adapt to changing conditions, (2) persist in sub-optimal conditions but with potentially significant physiological costs, (3) move to environmental conditions that suit their physiological tolerances by expanding or contracting their range in space (along latitudinal, depth, or intertidal gradients), or (4) adjust the timing of aspects of their life history (e.g., breeding events).
- Examples of responses include:
  - Observed northward shift of key species (including Humboldt squid, volcano barnacle, gray whales, bottlenose dolphins).
  - Changes in the timing of certain life cycle events, such as in spawning by marine fish to ensure maximum food availability for larval fish, and in breeding by seabirds to maximize prey abundance during chick-rearing.
- Certain habitats are of particular concern, such as benthic habitats (communities with a limited ability to move will have to adapt for survival) and island habitats (rising sea level and increased wave/storm intensity may permanently flood intertidal areas where seals and sea lions haul out, or shrink the area available for seabirds to nest and breed), and beach habitats (sea level rise and increased storminess can increase rates of shoreline erosion and retreat, as well as degrade habitat quality).

This document is intended to serve as a baseline for understanding relevant climate change impacts to habitats and biological communities within the study region. Sanctuary management intends to use this information to begin identifying priority management actions that will be taken over the next 10 years to address the impacts of climate change along the north-central California coast.

National Climate Assessment: Technical Inputs. U.S. Global Change Research Program (2011-2012). http://www.globalchange.gov/what-we-do/assessment/nca-activities/available-technical-inputs

Federal law requires a national climate assessment (NCA) to be submitted every four years to the President and Congress. The USGCRP, a collaboration of 13 federal science agencies, is responsible for organizing and administering the assessment. The NCA's responsibilities are to: (1) integrate, evaluate, and interpret the findings of the USGCRP; (2) analyze the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and (3) analyze current trends in global change, both human-induced and natural, and project major trends for the next 25 to 100 years. The third NCA was released in 2014.

As part of the process of preparing the assessment, individuals and teams were invited to submit technical inputs for consideration by the NCA Development Advisory

Committee. The NCA author teams had full discretion in deciding whether to cite any of the technical inputs. Available technical inputs, which address sectors (both individually and across sectors), regions (also individually and across regions), and adaptation, mitigation and decision support, are found online at the above URL. Selected technical input documents are summarized below.

National climate assessment technical report on the impacts of climate and land use and land cover change. Loveland T, et al. (2012). U.S. Geological Survey. U.S. Geological Survey Open-File Report 2012–1155. http://pubs.usgs.gov/of/2012/1155/

Land use encompasses the human activities and management practices for which land is used. Land use determines land cover (the status of vegetation, bare soil, developed structures and water bodies), which in turn changes surface albedo and transpiration, affecting the exchange of water, energy, and gases with the atmosphere—which can ultimately cause changes in regional temperature and precipitation patterns. The need to mitigate the adverse effects of weather and climate variability and change can force changes in land use and potentially land cover.

This report assesses how current and predicted changes in land use and land cover (LULC) affect weather, climate and other global environmental conditions and, in turn, how those conditions will change LULC. This assessment is based on current published, peer-reviewed, scientific literature and supporting data from both existing and original sources. It specifically investigates:

- The primary contemporary trends in land use and land cover in the U.S.
- The land-use and land-cover sectors and regions in the U.S. which are most affected by weather and climate variability
- How land-use practices are adapting to climate change
- How land-use and land-cover patterns and conditions are affecting weather and climate, including effects from agriculture and urbanization

These findings can be used to better assess land change and climate interactions in order to inform land management and adaptation strategies for future environmental change. The report also presents considerations for designing an ongoing national assessment of climate change and LULC impacts. Below are concluding remarks presented in this report:

- Maintaining the societal and ecological benefits drawn from land resources — land cover and land use—requires an integrated understanding of the links between land use-land cover and weather and climate. There is an increasing interest in this area of research.
- Where there is considerable capacity to provide near real-time monitoring of land use-land cover responses to climate, there is currently no systematic effort to monitor and evaluate climate-driven changes in land use and land cover. The basic elements needed for monitoring and assessment exist, and the next steps are to move beyond independent case studies and a rich assortment of technical

tools and data, and into a designed, integrated framework for ongoing national assessments.

A Workshop in Risk Based Framing of Climate Impacts in the Northwest: Implementing the National Climate Assessment Risk Based Approach. Dalton M and Mote P (workshop summary authors) (2012). http://downloads.usgcrp.gov/NCA/Activities/northwestncariskframingworkshop.pdf

The Northwest NCA Risk Framing Workshop (convened pursuant to a grant from the U.S. Geological Survey to develop input for the NCA) brought together carefully selected experts from the region to engage in a discussion of climate impacts through a risk frame, separately assessing the likelihood and consequences. Although the workshop was intended to examine climate impacts in the Northwest, the risk framework applied in assessing impacts can be applied elsewhere, and many of the impacts discussed are relevant to California. The objectives of this integrative workshop were threefold: 1) discuss and rank the likelihood and consequences of climate risks to the northwest region; 2) provide opportunity to help inform the NW chapter of the NCA; and 3) build capacity for a long term, sustained regional assessment process. This workshop, held in Portland, Oregon, served as an initial step toward identifying key risks and vulnerabilities to highlight in the Northwest chapter.

The risks considered in this workshop were: 1) extreme heat events; 2) changes in hydrology and water resources; 3) wildfires; 4) ocean temperature and chemistry changes; 5) sea level rise and coastal hazards; 6) shifts in distributions of plants and animals; 7) increase in invasive species, pests, and diseases; and 8) extreme precipitation and flooding. A discussion of the likelihood and consequences of each of these risks is summarized in this report, along with a summary of survey rating questions (a written survey was conducted during the workshop); if input was provided, case study examples, gaps in knowledge, special considerations, and references are also included.

Climate and Energy-Water-Land System Interactions Technical Report to the U.S. Department of Energy in Support of the National Climate Assessment. Skaggs R, et al. (2012). PNNL-21185. Pacific Northwest National Laboratory. Richland, WA. http://www.pnnl.gov/publications/abstracts.asp?report=404278

This report focuses on climate and energy-water-land (EWL) system interactions and provides a framework to characterize and understand important elements of climate and EWL system interactions. It presents a long-term research program to address the priority scientific challenges and gaps. Two discrete case studies are used to explore the climate-energy-water-land interface with the broad themes of (1) extreme events and (2) regional differences. These case studies help demonstrate unique ways in which EWL interactions can occur and be influenced by climate, and illustrate decision-making considerations. Key findings from the report are summarized below.

Characterization of climate and energy-water-land system interactions

- Population growth and economic and social development are major drivers of the demand for energy, land, and water resources within the interdependent climate and EWL system.
- The interdependencies of climate and the EWL system can be characterized by the three bilateral interfaces of energy-water, energy-land, and land-water. Each bilateral interface consists of linkages representing the supplies, end-use demands, and associated functional relationships between the two. Integration of these three interfaces—and the interdependencies and feedbacks among them and climate—is needed in a comprehensive assessment.
- Much of our understanding of climate impacts on the EWL system is derived from limited observations of bilateral interface responses to climate variability. The concept of EWL interfaces can help identify the relative degree of risks and vulnerabilities to the effects of climate variability and change.

Energy-water-land interfaces: Resource interdependencies and interactions with climate

- Focusing on sector-to-sector interfaces alone does not adequately capture the complexity and importance of the EWL system. The many bilateral interfaces form a dynamic set of interacting processes linked through a complex network of feedbacks.
- Competition for water is the most straightforward conflict linking energy, water, and land (e.g., simultaneous demand for thermoelectric generation, irrigation, environmental flows).
- Extreme climate events such as drought and associated heat waves have important impacts on the EWL interfaces.
- Due to differences in climate, energy, water and land, regions of the U.S. will be impacted differentially by climate change, requiring different adaptation and mitigation strategies, which in turn have significant implications for EWL dynamics. California, for example, with its abundant renewable resources, would have a greater expansion of its electricity production with wind, solar, geothermal, biomass and small hydroelectric resources, as compared to the Gulf states which have limited renewables.

Risk, uncertainty, and vulnerability associated with climate impacts on energy-water-land interfaces.

- Risk, uncertainty, and vulnerability at the EWL interfaces generally have the following characteristics: (1) they are broader in scope; (2) they can be amplified or attenuated across sectors; (3) they have altered temporal and spatial dynamics; and (4) they manifest during extreme events.
- Awareness of the above four characteristics can enable monitoring and assessment mechanisms to anticipate and avoid or correct unintended consequences; more effective emergency planning and response can be put in place by understanding the sources of those consequences.
- Perhaps the biggest gains will come by increasing our understanding of human response and behavior to climate change and decisions concerning climate change,

identifying the trigger points where low-probability events within one sector can become high-consequence events in other sectors, and in identifying and understanding the amplification, attenuation, and feedback mechanisms that create unintended and unanticipated consequences.

Climate mitigation and adaptation at the energy-water-land interfaces

- Understanding the EWL nexus is central to the effective design, selection, implementation, and monitoring of adaptation and mitigation strategies. Since almost all mitigation options lie within either the energy or land sectors (that is, mitigation addresses emissions arising from the supply and demand for energy and land), mitigation options are affected by EWL relationships.
- Adaptation options designed to reduce vulnerability to climate impacts in one EWL sector affect, and are affected by, EWL linkages. Some adaptation measures reduce demands on EWL endowments (e.g., water-use efficiency), while others may increase them (e.g., desalinization).
- Understanding how mitigation and adaptation strategies relate to the EWL interfaces facilitates the evaluation not only of the net impact of individual measures, but also the compound effects of concurrent implementation, either intentionally or as an outcome of the uncoordinated actions of independent parties.
- Some sector-specific mitigation and adaptation measures have the potential to provide synergistic “win-win” opportunities to enhance climate mitigation or adaptation objectives across one or more other sectors in the nexus. Others may have negative impacts on mitigation or adaptation potential in other sectors.

Research needs associated with climate impacts on energy-water-land interfaces

- A major complication in understanding and responding to climate changes is that they are often characterized by multiple interactions, feedbacks, and tradeoffs among different human activities and environmental processes.
- Simulating and understanding the interactions and feedbacks among climate and the EWL system requires not only accurate representations of each individual sector, but also a detailed understanding of the scale-dependent interactions among them.
- Addressing the climate-EWL related questions that regional decision makers are asking will require the development of models capable of evaluating different adaptation strategies, testing different mitigation options, and accounting for the tradeoffs, co-benefits, and uncertainties associated with these actions or combinations of actions—such as how technology cost, performance, and availability will impact results.
- Research needs include:
    - A new class of models, measurements and observations to allow meaningful analyses of the EWL interfaces
    - New strategies for understanding and quantifying uncertainty
    - Robust metrics for benchmarking model performance and data systems
    - New methods for parsing sparse data or extracting information from existing data for those regions lacking the necessary data

- New research and modeling capabilities that account for potential future environmental constraints, economic limitations and scenario development in the context of climate
- New tools that provide stakeholders with information on near-term consequences and long-term implications of mitigation or adaptation options
- Accounting for natural boundaries in gridded calculations and observations

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Coastal Impacts, Adaptation and Vulnerability: A Technical Input to the 2013 National Climate Assessment. National Oceanic and Atmospheric Administration. Burkett VR and Davidson MA [Eds.] (2012). Washington, D.C: Island Press. http://www.cakex.org/virtual-library/coastal-impacts-adaptation-and-vulnerabilities-technical-input-2013-national-climate

This report examines the known effects and relationships of climate change variables on the coasts of the U.S. It describes the impacts on natural and human systems, including several major sectors of the U.S. economy, and the progress and challenges to planning and implementing adaptation options. It notes that climate change is altering all types of ecosystems and impacting human welfare and health; its effects are highly varied and pronounced along coasts, and likely to accelerate in the coming decades. Below are the key findings from each chapter of the report.

- ***Introduction:*** Environmental changes due to development compromise the ability of the coasts to continue to provide a multitude of benefits, including food, clean water, jobs, recreation, and protection from storms. The benefits are, in some cases, further impacted by the changing climate.

- ***Physical impacts***
  - Large urban centers and important infrastructure (such as seaports, airports, power plants, and military bases) along U.S. coastlines are vulnerable to varying degrees to impacts of global warming such as sea-level rise, storms, and flooding.
  - Warming and some environment-related changes are occurring globally at rates greater than can be expected due to natural processes. Some of these changes are likely due in large part to anthropogenically increased atmospheric concentrations of greenhouse gases and altered land surface properties.
  - Many independent scientific studies conclude that the changes are consistent with global warming.
  - Most coastal landforms (such as barrier islands, deltas, bays, estuaries, wetlands, coral reefs) are highly dynamic and sensitive to even small changes in physical forces and feedbacks, such as warming, storms, ocean circulation, waves and currents, flooding, sediment budgets, and sea-level rise.
  - The effects of sea-level rise on coasts vary considerably from region-to-region and over a range of spatial and temporal scales.
  - The gradual inundation from recent sea-level rise is evident in many regions.
  - Sea level change and storms are dominant driving forces of coastal change.

- No coordinated, interagency process exists in the U.S. for identifying agreed upon global mean sea-level rise projections for the purpose of coastal planning, policy, or management, even though this is a critical first step in assessing coastal impacts and vulnerabilities.
- Global sea level rose at a rate of 1.7 millimeters/year during the 20th century, rising at a faster rate (over 3 millimeters/year) in the past 20 years. Scientific studies suggest that global mean sea level will rise 0.2 to 2 meters by the end of this century.
- Variability in the location and time-of-year of storm genesis can influence land-falling storm characteristics; even small changes can lead to large changes in land falling location and impact.
- Although sea-level rise and climate change have occurred in the past, the increasing human presence in the coastal zone will make the impacts different for the future.
- Observations continue to indicate an ongoing, warming-induced intensification of the hydrologic cycle; this will likely result in heavier precipitation events and, combined with sea-level rise and storm surge, increased flooding severity in some coastal areas, particularly the northeast U.S.
- Temperature is primarily driving environmental change in the Alaskan coastal zone.
- Large reserves of methane bound-up in Alaska's frozen permafrost are susceptible to release if the Arctic continues to warm.

- ***Vulnerability and impacts on natural resources***
  - Multiple stressors interact at the coast, directly impacting natural resources in complex ways, and are subject to nonlinear changes and tipping points. Linkages with human systems heavily influence many of the responses.
  - Wetland ecosystems are vulnerable to relative rise in water levels and projected increases in storm activity in zones of significant human use.
  - Mangrove range will expand as minimum temperatures increase.
  - Coastal forests will migrate upslope and poleward where they would be able to keep pace with changing habitat conditions.
  - The structure and functioning of estuary and coastal lagoon systems will change with alterations in habitat suitability and the timing of long-standing processes.
  - Dynamic barrier island landscapes naturally migrate in response to storm activity and sea-level rise, a process confounded by human alterations.
  - Because of altered sediment supplies and local subsidence, deltas and the biodiversity they support are at risk to drowning during rising sea levels.
  - Mudflats are susceptible to threshold changes caused by the combined effects of sea-level rise, temperature, land use, altered flows, and increased nutrient runoff.
  - Complex interactions between physical and biological factors, which make responses to climate change difficult to predict, have been demonstrated in rocky shore communities.
  - Sea ice ecosystems are already being adversely affected by the loss of summer sea ice, and further changes are expected.

- ***Vulnerability and impacts on human development***
  - Expanding economic and human population zones along the coast significantly increase the risk of harm, exposing already vulnerable communities to the impacts of climate change.
  - The full measure of human vulnerability and risk is comprised of the vulnerabilities of human development, economic sectors, associated livelihoods, and human well-being.
  - Storm surge flooding and sea-level rise pose significant threats to public and private infrastructure for energy, sewage treatment, clean water, and transportation of people and goods, thus increasing threats to public health, safety, and employment in the coastal zone.
  - Systematic incorporation of climate risk into the insurance industry's rate-setting practices and other business investment decisions could present a cost-effective way to deal with low probability, high severity weather events.
  - Expected public health impacts include a decline in seafood quality, shifts in disease patterns and increases in rates of heat-related morbidity.
  - The Department of Defense requires actionable climate information and projections at mission-relevant temporal and spatial scales to maintain effective training, deployment, and force sustainment capabilities on coastal installations.

- ***Adaptation and mitigation***
  - Efficiency of adaptation can be improved through integration into overall land use planning and ocean and coastal management.
  - In some cases, adaptation is being directly integrated, or mainstreamed, into existing decision-making frameworks regarding zoning and floodplain, coastal, and emergency management, but these frameworks are not always a perfect fit and sometimes existing laws pose a barrier to implementation.
  - Tools and resources to support adaptation planning are increasing but technical and data gaps persist.
  - Although adaptation planning has an increasingly rich portfolio of case studies that contribute to shared learning, the implementation of adaptation plans has proceeded at a much slower pace.
  - Elements commonly found in adaptation plans include vulnerability assessments, monitoring and indicators, capacity building, education and outreach, regulatory and programmatic changes, implementation strategies, and a sector-by-sector approach.
  - Although state and federal governments play a major role in facilitating adaptation planning, most coastal adaptation will be implemented at the local level.

Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector. Vose JM, Peterson DL, and Patel-Weynand T (Eds.) (2012). Gen. Tech. Rep. PNW-GTR-870. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, OR.
http://www.usda.gov/oce/climate_change/effects_2012/effects_forest.htm

This report is a scientific assessment of the current condition and likely future condition of forest resources in the U.S. relative to climatic variability and change. It includes descriptions of key regional issues and examples of a risk-based framework for assessing climate-change effects. The report found that it is difficult to conclude whether recently observed trends or changes in ecological phenomena are the result of human-caused climate change, climatic variability, or other factors. Regardless of the cause, forest ecosystems in the U.S. at the end of the 21st century will differ from those of today as a result of the changing climate. Highlighted below are key points discussed in this report:

- ***Effects of climate change on ecosystem structure, function, and services***
  - A gradual increase in temperature will alter the growing environment of many tree species throughout the U.S., reducing the growth of some species (especially in dry forests) and increasing the growth of others (especially in high-elevation forests).
  - In many species, tree growth and regeneration may be affected more by extreme weather events and climatic conditions than by gradual changes in temperature or precipitation (the high genetic diversity of most tree species confers tolerance of a broad range of environmental conditions, including temperature variation). Increased atmospheric CO_2 and nitrogen deposition will potentially alter physiological function and productivity of forest ecosystems, with considerable variation in response among species and regions.
  - The effects of climate change on water resources will differ by forest ecosystem and local climatic conditions, as mediated by local management actions.
  - Forest growth and afforestation in the U.S. currently account for a net gain in carbon (C) storage, offsetting approximately 13 percent of the nation's fossil fuel CO_2 production.
  - Future changes in forest ecosystems will occur on both public and private lands and will challenge their ability to provide ecosystem services, especially as human populations continue to grow and demands for ecosystem services increase.

- ***Effects of disturbance regimes***
  - Altered disturbance regimes, often occurring with increased frequency and severity, will cause the most rapidly visible and significant short-term effects on forest ecosystems.
  - Wildfire will increase throughout the U.S., causing at least a doubling of area burned by the mid-21st century.

- Insect infestations, such as the current advance of bark beetles in forests throughout the Western U.S. and Canada, will expand, often affecting more land area per year than wildfire.
- Invasive species will likely become more widespread, especially in areas subject to increased disturbance and in dry forest ecosystems.
- There will be increased flooding, erosion, and moving of sediment into streams, highly variable in space and time.
- Increased drought will exacerbate stress complexes that include insects, fire, and invasive species, leading to higher tree mortality, slow regeneration in some species, and altered species assemblages.

- ***Regional effects of climatic variability and change***
  - In the Southwest:
    - Disturbance processes facilitated by climatic extremes, primarily multiyear droughts, will dominate the effects of climatic variability and change on both short- and long-term forest dynamics.
    - Although diebacks in species other than pinyon pine (*Pinus edulis* Engelm.) are not widespread, large fires and insect outbreaks appear to be increasing in frequency and spatial extent.
    - Increased disturbance from fire and insects, combined with lower forest productivity at most lower elevation locations, will result in lower C storage in most forest ecosystems. This may keep many low-elevation forests in younger age classes in perpetuity.
    - Increased fire followed by high precipitation (in winter in California and in early summer in much of the rest of the Southwest) may result in increased erosion and downstream sediment delivery.
  - Other regions discussed in this report are: Alaska, Hawaii and the Pacific territories, Northwest, Great Plains, Midwest, Northeast, and Southeast.

Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment. Cooperative Report to the 2013 National Climate Assessment. Staudinger MD et al. (2012). http://downloads.usgcrp.gov/NCA/Activities/Biodiversity-Ecosystems-and-Ecosystem-Services-Technical-Input.pdf

This technical input to the 2013 NCA includes consideration of ecosystem services, interaction between climate change and other environmental stressors, and a discussion of the rapidly advancing field of climate adaptation.

Key findings include:

- Ecosystems are already more stressed than at any previous time in human history, and climate change almost always exacerbates the problems caused by other environmental stressors.

- Climate change is influencing species' shifts in geographic range, distribution, and life cycle events faster than previously thought. These changes can substantially alter ecosystem structure and function. Species that are unable to shift their geographic distributions or have narrow environmental tolerance are at increased risk of extinction, and there is increasing evidence of population declines and local extinctions that can be attributed to climate change. Range shifts will result in new community assemblages, and promote interactions among species that have not existed in the past.

- Changes in precipitation and extreme events can cause ecosystem transitions, increase downstream transport of nutrients and pollutants, and overwhelm the ability of natural systems to mitigate harm. In addition to ecosystem restructuring, drinking water quality is likely to be impacted as high rainfall and river discharge lead to higher levels of nitrogen in rivers and greater risk of waterborne disease outbreaks.

- Changes in the winter, such as soil freezing, snow cover, and air temperature, affect carbon sequestration, decomposition, and export. Seasonally snow-covered regions are especially susceptible to changes in ecosystem structure and function caused by climate change following small changes in temperature and precipitation.

- Sea level rise and more severe storms threaten the ecosystem services provided by coastal habitats.

- Ecological monitoring efforts need to be improved and better coordinated among Federal and State agencies to provide information to support ecological research, management, assessment and policy.

- Climate change responses in other sectors (such as agriculture, energy and transportation) are creating new ecosystem stresses, but incorporating ecosystem-based approaches can improve their efficacy.

- Climate adaptation has received an increase in attention, and has become emphasized in biodiversity conservation and natural resource policy and management. Biodiversity conservation requires landscape-scale conservation, connectivity among protected habitats, and sustaining ecological functioning of working systems. Agile and adaptive management approaches are increasingly important for land and water managers, and risk-based framing and stakeholder-driven scenario planning will be essential in enhancing responses to climate change.

The report concludes that regular and ongoing assessments are needed to track changes, predict future changes, and inform response strategies. Proposed actions for the sustained assessment of biodiversity, ecosystems, and ecosystem services include: 1) Identify a core set of widely recognized, policy-relevant questions about climate change impacts, 2) establish a broader ecosystem assessment process and framework, and 3) align climate monitoring, modeling, and assessment activities with those for biodiversity and ecosystem services.

National Climate Assessment Indicators: Background, Development, & Examples. Janetos AC, Chen RS, Arndt D and Kenney MA (contributing lead authors) (2012). http://downloads.usgcrp.gov/NCA/Activities/NCA-Indicators-Technical-Input-Report-FINAL--3-1-12.pdf

This paper establishes a rationale for developing a system of indicators for an ongoing national climate assessment process. It lays out a framework for a set of climate-related indicators that will provide information on greenhouse gases, variability and change in the climate system, status and trends of important sectors that are known to be sensitive to climate variability, and response strategies.

The following categories and potential indicators were identified in the framework process:

- Greenhouse gas emissions and sinks
  - Possible indicator: U.S. greenhouse gas emissions
- Atmospheric composition
  - Possible indicator: the Aggregated Greenhouse Gas Index
- Physical climate variability and change
  - Possible indicators: temperature and precipitation, the Climate Extreme Index, and the U.S. Drought Monitor
- Sectors and resources of concern
  - Possible indicators: the state of the arctic sea ice, net primary productivity trends (i.e., the annual net biomass growth of all plant material on a unit of land), agricultural indicators (such as crop distribution maps), bioclimatic indicators of spring, heat-related mortality as a climate change human health indicator, the Residential Energy Demand Temperature Index, and the Social Vulnerability Index

The report did not present these indicators as a final set, because an overall process for indicator selection with participation from important stakeholders has not yet been undertaken. This initial set of indicators reveals both where there is a substantial amount of well-documented information, and where there are important gaps that must be filled by subsequent research. Major gaps exist in areas related to societal indicators, human well-being, and health. Of particular concern are indicators that are relevant to understanding the nation's progress on climate adaptation, and ensuring that what is already known about greenhouse gas mitigation can be captured in an indicator context.

Finally, the report states that, although there are already many examples of programs and indicators, their purpose and relevance to decision-making processes are not always clear. Many existing indicators (and the programs that support them) for climate-related information have been created primarily for educational, research, and informational purposes. While some of the climate-related indicators for the physical climate system are integrated into operational decision-making, the majority of those

examined to date have been created to illuminate scientific issues or provide information more generally. Ecosystem indicators, too, have varied between being largely informational (e.g. the Heinz Center State of the Nation's Ecosystem) and being part of a resource management process (USFS forest sustainability indicators). Understanding the desires of different stakeholder communities, and their needs either for operational decision-making, policy-making, scientific research, or public information remains a serious strategic challenge for the NCA.

Water Resources Sector Technical Input - Interim Report in Support of the U.S. Global Change Research Program 2014 National Climate Assessment. Brewer M, Brown TC, McNutt C (lead authors) (2012, updated 2013). U.S. Army Corps of Engineers, Institute for Water Resources Alexandria, VA. http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/2013-R-10_Water_Resources_Sector_TIR.pdf

This report is an assessment of recent, relevant information on the effects of climate change on freshwater resources. The focus of this report is primarily on observations and projections of change that are well-documented, peer-reviewed, and useful to assess impacts of climate change on freshwater resources, including key vulnerabilities, and the development of adaptation and mitigation strategies. The report is organized by six key issues: (1) Precipitation patterns and intensity; (2) Surface water, including streamflow, snowmelt, and floods; (3) Groundwater, including soil moisture; (4) Water Quality; (5) Water Resources Management Implications, and (6) Adaptation. Research needs are also presented.

Highlighted below are some main points relating to these key issues:

1. Precipitation
    - Seasonal and annual precipitation totals across the continental U.S. (CONUS) have increased or remain unchanged in the winter season over the period of record from 1895-2011.
    - Precipitation intensity is expected to change with a warming climate. In addition to climatological and theoretical reasons, both observational and modelled evidence support this anticipated change.
    - At roughly two-thirds of the Historical Climatology Network stations across the CONUS, there is a positive trend in the 2-, 5-, and 10-year return-period for daily rainfall from 1950-2007. There is also a regional pattern to the trends with the Northeast, western Great Lakes, and the Pacific Northwest exhibiting dominantly positive trends. This means that the length of time between extreme events is getting shorter, or events are occurring more frequently. For most regions, there is a 20% reduction in the length of time between extreme events.
    - There has been an increase in the number of no-rain periods lasting a month or longer in the eastern U.S. in the summer over the past several decades.
    - A northward shift of storm tracks has resulted in regional changes in the frequency of snowstorms in the U.S.

- There is an increasing trend in national areal coverage of drought conditions since 1971, but there is no trend for 1900-2011.
- General circulation models (GCMs) agree in most locations and seasons on the sign of the changes in temperature, but projections of changes in precipitation are more uncertain.
- Both winter extreme precipitation and winter mean precipitation are projected to increase in the northern U.S. and decrease in the southern U.S. in one study; the increase in the extreme precipitation is projected to be greater than that for mean precipitation. A different trend is projected in another study, which found that increases in summer temperatures were associated with decreases in summer precipitation of up to 0.75mm (0.03 in) per day in the 2020–2039 period.

2. Surface water
   - Declines in spring snowpack have been observed in much of the mountain west. In snowmelt-dominated systems of the Northeast and Western U.S., changes have been observed in streamflow timing and quantity, attributed to changes in the form of precipitation and temperature due to natural climate variability and to human-induced global warming.
   - Snow water equivalent (SWE)--a measure of the water held in the snowpack–has decreased at many stations in the western U.S., accompanied by a general increase in winter precipitation over the past 50 years, indicating more precipitation occurring as rain rather than snow.
   - Flood producing precipitation increased over the latter half of the 20th century, attributed to anthropogenic climate change and a warmer climate in general.
   - Streamflow projections indicate that significant changes that vary by region are likely for the future throughout the U.S.
   - Cool season runoff is projected to increase over West Coast basins from California to Washington and over the North-Central U.S., but little change is projected for the Southwest.

3. Groundwater
   - In many areas, including California and the southeastern U.S., increases in groundwater use during surface water shortages have been dramatic. Global groundwater depletion is in part contributing to sea level rise though aquifer impaction and land subsidence, as well as increased freshwater discharge to the ocean.
   - Groundwater conditions and withdrawal rates in the U.S. generally are poorly monitored
   - There have been few direct projections of groundwater conditions in response to climate change, but projections of surface water shortages likely mean greater reliance on groundwater for water supplies, which, in turn, could mean less groundwater discharge to the surface system.

4. Water Quality
   - Water quality is a result of natural physical, chemical, and biological processes interacting with human use and management of land and water resources.

Changes in climate and hydrology can have direct and indirect effects on water quality.

- Temperature is a fundamental control on biological processes in streams. Stream temperature has been increasing many places in recent decades even without land cover or land use change, although rates of warming are generally slower than rates of air temperature increases.
- Increased air and water temperatures are likely to increase stratification in many lakes and reservoirs, reducing mixing frequency and leading to declining oxygen concentrations.
- A more vigorous hydrologic cycle including increased precipitation intensity will likely increase movement of sediment, nutrients and pollutants to downstream ecosystems.
- The transmission and proliferation of microbial and chemical contaminants could increase as a result of changes in air and water temperatures and changes in runoff.

5. Water Resources Management Implications
   - Future climate change can have wide-ranging effects on water management and use. The report discussed implications on the following systems: water infrastructure, aquatic environments, flooding, navigation, hydropower, water demand, water supply and shortage, and water and wastewater treatment.

6. Adaptation
   - Adaptation entails two broad kinds of endeavors: building adaptive capacity; and implementing changes in response to specific vulnerabilities. Options for both are presented in the report.

7. Research Needs
   - Addressing research needs in the following areas will improve water resources management in the future:
     - Climate information: improving projections at different spatial and temporal scales; better representations of climate response globally and at scales relevant to water resources management; better representation of hydrological extremes.
     - Hydrologic information: increased knowledge of ecosystem response to changes in climatic drivers; better understanding of social system responses (e.g. population dynamics, potentially competing objectives; land use changes).
     - Water resources and decision making: improved monitoring networks; characterizing uncertainties associated with approaches that utilize new assumptions of future climate; communicating such uncertainties to decision-makers.

Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment. Garfin G, et al. (Eds.) (2013). Southwest Climate Alliance. Washington, DC: Island Press. http://downloads.globalchange.gov/nca/technical_inputs/SW_Assessment_2013.pdf

This report summarizes current understanding of climate variability, climate change, climate impacts, and possible solution choices for the climate challenge for the southwest U.S. This region consists of six states—Arizona, California, Colorado, Nevada, New Mexico, and Utah—occupying an area of about 700,000 square miles, including vast stretches of coastline, an international border, and the jurisdictions of 182 federally recognized Native American tribe. Highlighted below are main points discussed in this report:

Observed Recent Climatic Change in the Southwest

- The southwest is warming.
- Recent drought has been unusually severe relative to droughts of the last century, but some droughts in the paleoclimate record were much more severe.
- Recent flows in the four major drainage basins of the Southwest have been lower than the twentieth century averages.

Projected Future Climatic Change in the Southwest

- Warming will continue, with longer and hotter heat waves in summer.
- Average precipitation will decrease in the southern Southwest and perhaps increase in northern Southwest.
- Precipitation extremes in winter will become more frequent and more intense (i.e., more precipitation per hour).
- Late-season snowpack will continue to decrease.
- Declines in river flow and soil moisture will continue.
- Flooding will become more frequent and intense in some seasons and some parts of the Southwest, and less frequent and intense in other seasons and locations.
- Droughts in parts of the Southwest will become hotter, more severe, and more frequent.

Recent and Future Effects of Climatic Change in the Southwest

- Natural ecosystems are being affected by climate change in noticeable ways. Animals and plants inhabiting these areas may need to adapt, change, or move.
- Coastal California is already being affected by climate change, and future climate-related change will become more notable if greenhouse gas emissions are not substantially reduced.
- Water is the limiting resource in the Southwest, and climate variability and change will continue to have substantial effects on water across much of the region. Reduction in water supplies can lead to undesirable changes in almost all human and natural systems including agriculture, energy, industry, forestry, and recreation.
- The Southwest's highly complex and often extreme geography and climate increase the probability that climate change will affect public health. Several potential drivers

of increased health risk exist only or primarily in the Southwest, and there is substantial variation in the sensitivity, exposure, and adaptive capacity of individuals and groups of people within the Southwest to climate change-related increases in health risks.
- Climate change has the potential to affect many other sectors and populations within the Southwest.

Choices for Adjusting to Climate and Climate Change
- Many options for responding to climate change in the Southwest have been, or are being, investigated, and are assessed in the report.

Key Unknowns
- Although there has been a substantial increase in the understanding of how the Southwest climate is changing and will change, and how this change will affect the human and natural systems of the region, much remains to be learned. Key challenges that contribute to uncertainties include:
  - A dearth of climate observations at high elevations and on the lands of Native nations.
  - Limited understanding of the influence of climate change on natural variability (e.g., El Niño–Southern Oscillation, Pacific Decadal Oscillation), extreme events (droughts, floods), and the marine layer along coastal California.
  - Imperfect climate models, downscaling, and resulting projections of the physical climate, especially given the diverse topography of the Southwest and its influence on regional climate.

Oceans and Marine Resources in a Changing Climate: A Technical Input to the 2013 National Climate Assessment. National Oceanic and Atmospheric Administration. Griffis R and Howard J (Eds.) (2013). Washington, D.C.: Island Press. http://cakex.org/virtual-library/oceans-and-marine-resources-changing-climate-technical-input-2013-national-climate-a

U.S. marine ecosystems and services are increasingly at risk from climate change and other human pressures. This report provides an assessment of the current and projected impacts of climate change and ocean acidification on the physical, chemical, and biological components and human uses of marine ecosystems under U.S. jurisdiction. It also provides assessment of the international implications for the U.S. due to climate impacts on ocean ecosystems and of efforts to prepare for and adapt to climate and acidification impacts on ocean ecosystems.

Highlighted below are key findings from the report:

- ***Climate-driven physical and chemical changes in marine ecosystems***
  - The Earth's oceans are warming as a result of increasing concentrations of atmospheric CO_2 and other greenhouse gases.

- Arctic ice has been decreasing in extent since the second half of the 20th century as a result of oceanic and atmospheric warming.
- The oceans play an important role in climate regulation through uptake and sequestration of anthropogenic CO_2.
- The oceans absorb CO_2, causing a series of chemical reactions that reduce ocean pH, a process known as ocean acidification.
- Ocean temperature and precipitation/evaporation rates have a direct influence on the Earth's weather and precipitation patterns that will likely increase storm intensity but decrease (or have no effect on) storm frequency.
- Given that climate and oceans interact to produce intra- and inter- decadal variability in ocean currents, upwelling, and basin-scale circulation, climate change will likely influence these important ocean features. The ability to detect and project such impacts is low.

- ***Impacts of climate change on marine organisms***
  - Throughout the U.S. ocean ecosystems, climate change effects (i.e., shifts in species distributions and ranges, effects on survival, etc.) are being observed that are likely to continue into the future. While impacts occur across a wide variety of taxa in all U.S. ocean regions, high-latitude and tropical areas appear most vulnerable.
  - The vulnerability and responses of marine organisms to climate change vary widely, leading to species that are positively impacted and species that are negatively impacted.
  - Climate change interacts with and can exacerbate the impacts on ocean ecosystems of non-climatic stressors such as pollution, overharvesting, disease and invasive species.
  - Past and current responses of ocean organisms to climate variability and climate change are informative, but extrapolations to future environmental conditions will differ from the range observed in recent history.

- ***Impacts of climate change on human uses of the ocean***
  - There are significant effects of climate change on all sectors pertaining to human uses of the ocean, including fisheries, energy, transportation and human health..
  - As a result of climate change, governance regimes for ocean environments and resources, as well as human health, will be challenged, and will likely have to change significantly in character and configuration.
  - Ocean "health," in terms of both the biophysical functioning of ocean ecosystems and the factors related to human health, will likely be affected by climate change.
  - Impacts of climate change on human social and economic systems provide critical insight into societal responses and adaptation options.

- ***International implications of climate change***
  - Many migratory species that span jurisdictional boundaries are exhibiting shifts in distribution and abundance.

- International partnerships will be necessary to ensure that monitoring protocols, management plans, and training programs are robust and coordinated for effective long-term implementation on shared marine resources.
- Although the Regional Fisheries Management Organizations are aware of climate change, only half of the organizations have addressed the issue.
- Climate change will affect transportation and security issues in both the short and long term.
- Coastal policy and management can be improved upon by accounting for the carbon sequestration value of coastal marine systems.

- ***Ocean management challenges, adaptation approaches, and opportunities in a changing climate***
  - Climate change presents both challenges and opportunities for marine resource managers and decision makers.
  - Ocean-related climate information, tools, and services are being developed to address the needs of decision makers and managers.
  - Opportunities for adaptation include incorporation of climate change into existing ocean policies, practices, and management efforts.
  - Progress is being made across the U.S. to enhance ocean resilience to climate change through local, state, national, federal, and non-governmental adaptation frameworks and actions.

- ***Sustaining the assessment of climate impacts on oceans and marine resources***
  - Sustained assessment of climate impacts on U.S. ocean ecosystems is critical to understanding current impacts, preparing for future impacts, and taking action for effective adaptation to a changing climate.
  - Assessing what is known about past, current, and future impacts is a challenging task for a variety of reasons. Many uncertainties and gaps still exist in understanding about the current and future impacts of climate change and ocean acidification on marine ecosystems.
  - A number of steps could be taken in the near term to address the challenges and advance assessment of impacts of climate change on oceans and marine resources, including:
    - Increasing the capacity and coordination of existing observing systems to collect, synthesize, and deliver integrated information on physical, chemical, biological, and social/economic impacts of climate change on U.S. marine ecosystems
    - Conducting a regional-scale assessment of current and projected impacts of climate change and ocean acidification on ocean physical, chemical, and biological components and human uses
    - Increasing data, information, and capacity needed to assess and project impacts of climate change on marine ecosystems
    - Build and support mechanisms for sustained coordination and communication between decision makers and science providers

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Regional Climate Trends and Scenarios for the U.S. National Climate Assessment Part 5. Climate of the Southwest U.S. Kunkel KE, et al. (2013). National Oceanic and Atmospheric Administration, National Environmental, Satellite, Data, and Information Service. NOAA Technical Report NESDIS 142-5. Washington, D.C. http://scenarios.globalchange.gov/sites/default/files/NOAA_NESDIS_Tech_Report_142-5-Climate_of_the_Southwest_U.S_0.pdf

The primary purpose of this document is to provide physical climate information about the southwest U.S. for potential use by the authors of the 2013 National Climate Assessment report. The southwest U.S. consists of six states—Arizona, California, Colorado, Nevada, New Mexico, and Utah—occupying an area of about 700,000 square miles, including vast stretches of coastline, an international border, and the jurisdictions of 182 federally recognized Native American tribe.

This document contains two major sections: 1) historical conditions in the Southwest U.S., with a focus on trends in temperature and precipitation metrics that are important in the region; and 2) climate model simulations for two scenarios of the future path of greenhouse gas emissions for the periods of 2021-2050, 2041-2070, and 2070-2099.

Observed Recent Climatic Change

- Climatic phenomena that have major impacts on the Southwest include drought, heat waves, winter storms, and floods.
- Average annual temperature has generally increased over the past 115 years, with a rise in the 1920s and 1930s, a prolonged level period, and a second rise from the mid-1970s to around 2000. Temperatures have leveled since then, and the past three years have been cooler than recent averages.
- Seasonal patterns are similar to annual patterns, with the recent period of elevated temperatures being most prominent in the spring and summer. Temperature trends are upward for each season, as well as the year as a whole, with magnitudes ranging from +0.1 to +0.21°F per decade.
- The wettest conditions occurred in the 1980s and 1990s, coinciding with a shift in Pacific climate in 1976, after which El Niño became much more frequent, but has dried in the last decade.
- Precipitation does not exhibit any obvious long-term trends, except for fall, which shows a slight upward trend (not statistically significant). There is no trend in the occurrence of extreme precipitation events.
- There is an overall downward trend in the occurrence of extreme cold periods, while the frequency of extreme heat waves has generally been increasing in recent decades.
- The length of the freeze-free season has increased substantially, now averaging about two weeks longer than during the 1960s and 1970s, and a whole month longer than in the early part of the 20th century.

Comparison of Projected Future Climatic Change with Historical Observations

- The observed rate of warming is similar to that simulated by the models; in particular, the observed acceleration of warming beginning in the. Simulations

indicate future warming in the 21st century to be much larger than the observed and simulated values for the 20th century.

- Observed variability of decadal mean precipitation is generally greater than the model simulations.

Climate Change and Agriculture in the United States: Effects and Adaptation. Walthall CL, et al. (2012). U.S. Department of Agriculture. USDA Technical Bulletin 1935. Washington, D.C.
http://www.usda.gov/oce/climate_change/effects_2012/CC%20and%20Agriculture%20Report%20(02-04-2013)b.pdf

U.S. agriculture, a $300 billion-a-year industry, is vulnerable to both direct effects of climate change, such as changes in temperature and precipitation, and indirect effects, such as pest activity and pollination services. This report presents information to frame and evaluate the vulnerabilities of U.S. agriculture to climate change and adaptation strategies. Timeframes for the assessments are the present, 25 years in future, and 90 years in future, focusing on the near future.

Crop response to changing climate:
Crops have temperature thresholds that define boundaries for growth and reproduction and optimum temperatures for each developmental phase. Warming temperatures may reduce crop yields or quality, increase crop failures, or shift crop production away from areas where temperatures no longer occur within these boundaries or during the critical time periods.

Controlled experiments show elevated atmospheric CO_2 increases plant growth while decreasing soil water-use rates. However, elevated CO_2 has mixed effects on yield and quality in some nitrogen-fixing plants, reducing the ability of pasture and rangeland to support grazing livestock. In field conditions, the growth stimulation effect of elevated CO_2 on crops is uncertain, but elevated CO_2 concentrations disproportionately stimulate the growth of weeds and will likely contribute to crop loss from weed pressure.

Increasing temperatures, increasing CO_2, and increasingly variable water availability (due to changing precipitation patterns) interact in complex ways to affect crop and forage plants.

Livestock response to changing climate:
Changing climatic conditions affect animal agriculture in four primary ways:

- Feed-grain production, availability, and price
- Pastures and forage crop production and quality
- Animal health, growth, and reproduction
- Disease and pest distributions

Livestock and dairy production may be more affected by changes in the number of days of extreme heat than by changes in average temperature. Livestock production systems providing shelter can reduce the risk associated with adverse weather events, but management and energy costs of temperature regulation will increase.

Warmer, more humid conditions promote insect growth and spread of diseases. Climate affects microbial populations and distribution, distribution of vector-borne disease, host resistance to infections, and food-borne diseases.

Effects of climate change on soil and water:
Seasonal precipitation affects the potential amount of water available for crop production, but factors influencing actual availability include soil type, soil water-holding capacity, and infiltration rate. Several processes that influence soil characteristics, such as organic matter accumulation and erosion, are sensitive to changing climate conditions.

Climate change will affect surface-water resources, which provide 58% of water withdrawals for irrigated production nationally. Temperature and precipitation shifts are expected to alter the volume, timing, and distribution of storm and snowmelt runoff to surface water bodies. The resulting shifts of water stress, crop yields, and crop competition will drive changes in cropland allocation and production systems. While aquifers are less sensitive to short-term weather patterns, groundwater recharge may be affected by changes in precipitation, streamflow, and soil water evaporation. Groundwater is a major irrigation water source in many states.

Extreme events:
Extreme climate conditions such as dry spells, sustained drought and heat waves can adversely affect crops and livestock. Droughts, periods of intense precipitation, and extremely hot nights are projected to increase. Extreme temperature events occurring during sensitive stages could affect plant growth and productivity. Within limits, animals can adapt to and cope with gradual thermal changes, but lack of conditioning to changing or adverse weather events can lead to catastrophic deaths and loss of productivity.

Adaptation:
US agriculture has demonstrated a remarkable ability to adapt to a variety of growing conditions amid social and economic changes, but these adaptations were made during a period of relative climatic stability and abundant resources. The agricultural system may be resilient to climate change over the short term due to flexibility to engage in adaptive behaviors, but yields of major crops are projected to decline by mid-century. The models projecting this decline often fail to take into account changes in pest activity, ecosystem services, and conditions limiting adaptation.

Projected climate changes may require major adjustments to production practices to remain productive and profitable, particularly for systems operating near their feasibility limits. In California's Central Valley, the most effective approach to managing climate

risk involves integrated changes in crop mix, irrigation methods, fertilization practices, tillage practices, and land management. Adaptation to pest pressures may include novel pesticide strategies, crop diversification, and management of biodiversity at field and landscape scales. Synergistic mitigation and adaptation policy frameworks will link carbon sequestration, greenhouse gas emissions, land use, water management, and sustainability of production systems. Constraints to adaptation arise from diverse ecological, social, and economic conditions.

Research needs:
The research needs are categorized within a vulnerability framework and address actions that would promote a better understanding of the exposure, sensitivity, and adaptive capacity of US agriculture to climate change. Research needs reported include improved projections of climate conditions on the scale of seasons to decades, process-level understanding of production systems to direct, indirect, and interacting effects of climate change, and development of new and existing adaptive management strategies for US agricultural stakeholders.

State of the Climate in 2012. American Meteorological Society (2013). Blunden J and Arndt DS (Eds.), *Bulletin of the American Meteorological Society*, 94(8):S1-S238. http://www.ncdc.noaa.gov/bams-state-of-the-climate/2012.php

The 23rd edition of this series puts weather and climate events of the year into historical perspective, and provides information on the state, trends, and variability of the climate system's many variables and phenomena. The editors note that this series is consciously conservative with statements of attribution regarding drivers of events on the scale of climate variability and change, and employs only widely-understood and established attribution relationships.

The series uses several "essential climate variables" to provide a broad representation of the climate system, including:

- **Fully monitored** variables that are observed and analyzed across much of the world, with a sufficiently long-term dataset with peer-reviewed documentation.
  - Atmospheric surface: air temperature, precipitation, air pressure, water vapor
  - Atmospheric upper air: earth radiation budget, temperature, water vapor
  - Atmospheric composition: CO_2, methane, other long-lived gases, ozone
  - Ocean surface: temperature, salinity, sea level, sea ice, current, ocean color, phytoplankton
  - Ocean subsurface: temperature, salinity
  - Terrestrial: snow cover, albedo
- **Partially monitored** variables, meeting some but not all of the above requirements
  - Atmospheric surface: wind speed and direction
  - Atmospheric composition: cloud properties
  - Ocean surface: CO_2, ocean acidity
  - Ocean subsurface: current, carbon

- Terrestrial: soil moisture, permafrost, glaciers and ice caps, river discharge, groundwater, ice sheets, fraction of absorbed photosynthetically-active radiation, biomass, fire disturbance

- **Expected to be added in the future**:
  - Atmospheric surface: surface radiation budget
  - Atmospheric upper air: wind speed and direction
  - Ocean surface: sea state
  - Ocean subsurface: nutrients, ocean tracers, ocean acidity, oxygen
  - Terrestrial: water use, land cover, lakes, leaf area index, soil carbon

Highlights from the annual report include:

- Globally, 2012 was among the 10 warmest years on record. The U.S. and Argentina experienced the warmest year on record.
- A weak La Niña dissipated in the spring. For the first time in several years, neither El Niño nor La Niña prevailed for the majority of the year.
- The Arctic continued to warm. Permafrost in northernmost Alaska reached record high temperatures, a new melt extent record occurred on the Greenland ice sheet, and Arctic sea ice extent reached a record low.
- The globally averaged sea surface temperature was among the 11 warmest on record.
- Ocean heat content remained near record high levels.
- The sea level has been increasing at an average rate of 3.2 ± 0.4 mm per year over the past two decades. In 2012, sea levels reached record highs.
- The ocean salinity trend that began in 2004 continued, suggesting that precipitation is increasing in already rainy areas and evaporation is intensifying in drier locations.
- Global tropical cyclone activity was near average; the North Atlantic was the only hurricane basin that experienced above-normal activity.
- Major greenhouse gas concentrations continued to rise.
- Cool temperature trends continue in the lower stratosphere. Some datasets place 2012 temperatures at record or near-record lows.

Chapter 2 features global-scale climate variables; Chapter 3 highlights the global oceans; and Chapter 4 includes tropical climate phenomena including tropical cyclones. Chapter 5 focuses on the Arctic, and Chapter 6 on the Antarctic. Chapter 7 provides a regional perspective authored largely by that region's climate specialists, including a section on North America.

The State of the Climate series presents not only snapshots of the climate, but of our capacity to monitor it. It emphasizes that the state of observing systems affects our ability to understand the complex, dynamic climate system and the phenomena embedded within it.

Explaining Extreme Events of 2012 from a Climate Perspective. Peterson TC, et al. (Eds.) (2013). *Bulletin of the American Meteorological Society*, 94(9):S1-S74. http://www.ametsoc.org/2012extremeeventsclimate.pdf

This collection of analyses of 12 extreme events that occurred around the world in 2012 represents current evolution in the field of attribution of extreme events and provides an opportunity to compare differing methodologies offered by different research groups. The differences provide insights into structural uncertainties, yet assessments of a single event largely agree.

Approximately half the analyses found evidence that anthropogenic climate change contributed to the extreme event examined. Findings of some of the assessments are summarized below:

- July 2012 was the warmest month on record for the contiguous U.S., accompanied by one of the most severe droughts on record. Much of the central and eastern U.S. experienced extremely high temperatures during spring and summer. The severe heat was likely due to changes in the surface energy balance caused by severe rainfall deficits and large-scale atmospheric conditions that reinforce dry, hot conditions at the surface and contribute to such rainfall deficits. Anomalies in surface temperature, atmospheric circulation and soil moisture were analyzed to quantify the likelihood of an event of this magnitude in the current and in preindustrial forcing regimes. The analyses suggest that the likelihood of extreme July temperature anomalies is greater in the current forcing, particularly over the north-central and northeastern U.S., where the mean occurrence of both 2012-magnitude temperatures and atmospheric conditions are four times more likely in the current forcing. The July 2012 soil moisture anomalies were substantial within the context of the preceding three decades, however important uncertainties in these data exist. Record rainfall deficits played a critical role in the 2012 severe heat, and occurrence of the most severe heat events is likely to continue to be strongly regulated by rainfall variability.

- Hurricane Sandy (October 29-30, 2012) did not have particularly strong winds, but its westward strike heading, massive storm surge, and damaging inundation led to record-setting impacts. Using tide-gauge water level statistics, estimates of the recurrence (also referred to as “return intervals”) of peak storm tide levels similar to Sandy’s were developed. Throughout the mid-Atlantic coast, sea level rise has decreased return intervals—that is, increased the likelihood—of Sandy-level events by one- to two-thirds compared to 1950 (when mean sea level was lower and required a larger storm tide to reach Sandy’s impact levels). Projections for the years 2050 and 2100 estimate even more frequent return intervals; for example, under the high emissions scenario south of Atlantic City, Sandy-level events are projected to recur annually by 2050, becoming less than annual events by 2100 under lower emissions (intermediate high and intermediate low) scenarios. Climate change-related sea level rise, vertical land motion, and ocean circulation variability have contributed to the more frequent return intervals. The projections imply that

events of lesser severity will produce impacts similar to Sandy's which is especially of concern given that the frequency and intensity of storms and surges are likely to increase in a warming climate.

Analyses were also presented for events occurring elsewhere, including:

- The rapid decline of Arctic sea ice extent in the early 21st century
- A cold spell in Western Europe failing to produce the expected ice thickness
- Summer 2012 precipitation anomalies in Europe
- The rainfall deficit in East Africa, including 2003-2012 rainfall trends
- July 2012 North China floods in the context of a longer-term drying tendency
- July 2012 heavy rainfall in southwestern Japan
- Increased rainfall in eastern Australia (March 2012 was the third wettest on record)

The report emphasizes that the challenge of attribution raises the question of the ability to predict forcing, and thus enable prediction of extreme events and mitigation of their effects.

Explaining extreme events of 2013 from a climate perspective. Herring, S. C., M. P. Hoerling, T. C. Peterson, and P. A. Stott (Eds.) (2014). *Bulletin of the American Meteorological Society*, 95(9):S1-S96.
http://journals.ametsoc.org/doi/pdf/10.1175/1520-0477-95.9.S1.1

Attribution of extreme climate events is a challenging science and one that is currently undergoing considerable evolution. The IPCC Fifth Assessment Report concluded that strong evidence exists for increases in some extremes worldwide since 1950, especially more frequent hot days and heavy precipitation events. However, natural variability plays a substantial role in individual events, and given the complexities of weather and climate processes, it remains difficult to authoritatively assess how climate change has affected the strength and likelihood of individual extremes. One goal of this report is to foster the development of scientific methods that can be applied operationally to explain the underlying physical processes causing extreme events and to place the event and associated processes in a historical context of climate variability and change.

In this paper, 20 different international research groups explored the causes of 16 different global events that occurred in 2013. Multiple groups chose to look at both the Australian heat waves and the California drought, providing an opportunity to compare and contrast the strengths and weaknesses of various methodologies. Sections 2, 3 and 4 of the report reported on the following:

- The extraordinary California drought of 2013/14: character, content and the role of climate change
- Causes of the extreme dry conditions over California during early 2013
- Examining the contribution of the observed global warming trend to the California droughts of 2012/13 and 2013/14

The following conclusions from the three sections were drawn concerning the California 2013/14 drought:

- The 2013/14 California drought was an exceptional climate event. A highly persistent large-scale meteorological pattern over the northeastern Pacific led to observationally unprecedented geopotential height (height of a pressure surface above mean sea-level) and precipitation anomalies over a broad region. The extreme geopotential height values in this region occur much more frequently in the present climate than in the absence of human emissions. Together, the complexity and severity of the observed drought impacts, coupled with the finding that global warming has increased the probability of extreme North Pacific geopotential heights similar to those associated with the 2013/14 drought, suggest that understanding the link between climate change and persistent North Pacific geopotential height events will be crucial in characterizing the future risk of severe drought in California.

- The state of California experienced extreme dry conditions during early 2013. When January and February are combined, January/February 2013 is ranked as the driest of the period 1895–2014. An assessment of the role of the long-term warming trend shows that it forces a high anomaly over the northeast Pacific, resulting in less North Pacific storms reaching California. Model results showed that concurrent sea surface temperature (SST) anomalies do force a predilection for dry events over California though considerably weaker than observed, suggesting that atmospheric internal variability accounted for the extreme magnitude of this climate event. The warming trend, however, also leads to increased atmospheric humidity over the northeast Pacific, thus facilitating wetter events over California. The above two effects appear to counteract each other, contributing to no appreciable long-term change in the risk for dry climate extremes over California since the late 19th century.

- In 2013/14, the North Pacific sea surface temperatures and the intensity of the upper troposphere geopotential height gradient reached historic maxima. The investigators concluded that these extremes appear very unlikely without anthropogenic climate change. They also noted that if SST and geopotential events like this become more common, California could experience more frequent droughts. In addition, the impacts of decreased Arctic sea ice may also contribute to these same atmospheric and sea surface temperature conditions that cause dry western U.S. winters.

Climate Sensitivity of the National Estuarine Research Reserve System.
Robinson P, et al. (2013). National Oceanic and Atmospheric Administration, National Estuarine Research Reserve System. Report to NOAA's Climate Program Office.
http://www.nerrs.noaa.gov/Doc/PDF/Research/130725_climate%20sensitivity%20of%20nerrs_Final-Rpt-in-Layout_FINAL.pdf

The National Estuarine Research Reserve System (NERRS) is a collection of 28 reserves located around the US and Puerto Rico, including three in California: Tijuana River, Elkhorn Slough, and the San Francisco Bay. These reserves are managed as a partnership between NOAA and the coastal states for long-term research, ecosystem monitoring, education, and coastal protection. The 1.3 million acres of estuarine and coastal habitat in the system represent a diverse set of ecosystems, which support ocean-dependent industries benefiting local economies and are subject to distinct anthropogenic and climate-related stressors. This report is the first national climate sensitivity analysis of U.S. estuaries, examining both the biophysical and socio-demographic sensitivities of reserve sites and the surrounding counties. The study 1) analyzes and synthesizes available information and data that describe the physical, ecological and socio-demographic attributes of the reserves, 2) identifies the dominant stressors that impact reserves and examines reserve ecological resiliency, and 3) categorizes reserves based on their potential sensitivities to climate hazards/variables, ecological resiliency, projected changes in temperature, and projected sea level rise.

Social Sensitivity to Climate Change: Climate sensitivity is defined here as whether and how a reserve or group of reserves will be affected by a change in climate conditions, measured over the particular environmental or social geography. Socioeconomic, demographic, and infrastructure data were used to assess sensitivity at the reserve and coastal county levels (counties in which at least 15 percent of the total land area was located within the US coastal watershed or within a coastal sub-basin).

- Reserves in the Gulf of Mexico or the West Coast were found to generally exhibit higher social sensitivity to climate change than those on the East Coast. Social sensitivity is very high at Elkhorn Slough, high at Tijuana River, and moderate at San Francisco Bay. The patterns in reserve social sensitivity around the country are related to differences in each reserve community's cultural barriers, dependence on natural resources, labor characteristics, and income levels. Reserves with higher socio-demographic sensitivity often exhibited one or more of the following characteristics: greater employment within natural resource-dependent extractive industries; lower per capita income levels and median home values; higher percentage of Hispanic and/or American Indian residents; and higher percentage of the population less than high school educated.

- Analysis at the county level revealed spatial heterogeneity in social sensitivity—that is, counties with low, moderate, and high sensitivity are commonly located near each other. However, portions of California, Florida, Texas and Alaska have areas of very high social sensitivity, which were often next to low sensitivity areas.

Reserve Ecological Resiliency: Ecological resiliency is defined here as a measure of the ability of an ecological system to return to its original state in a timely manner following an impact. Since comprehensive direct measures of ecological stress and integrity are not available, reserve staff expert input was used to develop estimated measures. Staff provided insights related to: (1) ecological integrity at the reserves; (2) the overall ecological stress the reserves are experiencing; (3) key ecological stressors;

(4) the relative contributions of key ecological stressors to overall ecological stress levels; and (5) causal factors related to the key ecological stressors. The largest contributors to reserve ecological stress include toxic contaminants; storm impacts; invasive species; habitat fragmentation; sediment loading and coastal shoreline erosion. Causal factors most frequently identified—including residential development, past land use and population growth—underscore the impact anthropogenic activities have on the reserves. It is expected that reserves with lower integrity ratings and higher stress would be less resilient and therefore have greater vulnerability to climate change. All three California NERR sites exhibit very low relative ecological resiliency.

Biophysical Sensitivity to Climate Variability: Non-climatic human activities and climate variability and change are the two dominant forces capable of disrupting the form, function, and ecosystem services provided by estuarine ecosystems. Their combined effects can dramatically alter estuarine environments, causing, among other things, changes in basic environmental conditions such as salinity, temperature and alkalinity. Sensitivity of biophysical water conditions thus represents a measure of dynamic responsiveness to climate change. The NERRS Biophysical Sensitivity Index (BpSI) is a relative scale developed to assess the relationship of climate and water quality at the reserve level. The strongest individual relationships were found for the comparison of air temperature to water temperature and the comparison of precipitation to specific conductivity. Reserves characterized as having very high and high biophysical sensitivity relative to all the reserves were scattered around the country; the only regional trend noted is that nearly all reserves with moderate sensitivity are located on the East Coast. Only four reserves have biophysical sensitivity classified as High or Very High. Relative biophysical sensitivity is very high at Tijuana River and low at Elkhorn Slough. Some sites, including the San Francisco, were omitted from this analysis for lack of uniform data sets.

Synthesis of NERRS Climate Sensitivity, Vulnerability, and Exposure: The five climate sensitivity and vulnerability indices used in this report include social sensitivity, biophysical water conditions, ecological resiliency, projected sea level rise, and projected air temperature rise. Synthesis shows that these indicators do not co-vary across the NERRS, and reserve managers will have to consider specific applicable stressors and plan management strategies accordingly. The synthesis predicts:

- All reserves will be impacted by climate change. Sea level rise is a concern across all regions, and temperature change is a concern over most regions.

- Social sensitivity is of particular concern along the West Coast and at isolated reserves in other regions.

- Biophysical sensitivity is of highest relative concern at isolated reserves in the Southeast and on the West Coast. Relevance of biophysical sensitivities will be determined by natural resource management objectives at each reserve.

- Several reserves exhibit particular climate change sensitivity. The highest overall risk for climate change impacts is found at the Tijuana River reserve, followed by Waquoit Bay (MA).

  The Tijuana River reserve is the only site exhibiting a relatively high likelihood of potential climate change impacts for all five indices. The Tijuana River watershed features high-density housing and four water reservoirs, and covers mostly Mexican land. Management of the reserve for potential climate change impacts will require international cooperation and could prove challenging.

The work presented in this report was intended to be foundational to inform future analyses. The authors state that by using a process like the one presented in this report, a multidisciplinary and collaborative approach can be employed and applied to estuarine networks outside the NERRS. Knowledge of the relationship between water quality variables and climate can be strengthened by the centralization and standardization of data related to observation stations and watershed characteristics. Finally, the authors note that estuarine sensitivity to impacts of short-term weather events, such as severe storms, should be analyzed.

Abrupt Impacts of Climate Change: Anticipating Surprises. Committee on Understanding and Monitoring Abrupt Climate Change and Its Impacts; Board on Atmospheric Sciences and Climate; Division on Earth and Life Studies; National Research Council (2013). http://www.nap.edu/catalog.php?record_id=18373

This report examines what is currently known about the risks of climate change on a global scale, identifies potential threats, and proposes improved monitoring and warning schemes to help prepare for both known and unknown abrupt changes. It focuses on abrupt climate changes and abrupt climate impacts that have (or may have) the potential to affect the physical climate system, natural systems, or human systems, often affecting multiple interconnected areas of concern. The primary timescale of interest is years to decades. A key characteristic of these changes is that they can come faster than expected, planned, or budgeted for, forcing more reactive, rather than proactive, responses. Major findings on abrupt impacts analyzed in the report are summarized below:

- ***Abrupt changes already underway***
  - *Disappearance of late-summer arctic sea ice:* Dramatic decreases in the extent and thickness in the arctic sea ice are well documented. For instance, satellite data from the National Snow and Ice Center show substantial decreases in late-summer Arctic sea ice extent since the satellite record began in 1979. The most recent seven summers have shown significantly lower sea ice cover. Projections from climate models suggest that ice loss will continue in the future, with a complete loss of late-summer arctic sea ice potentially occurring in the next several decades.

- *Increases in extinction threat for marine and terrestrial species:* Certain climate attributes, such as the number of frost-free days, length and timing of growing seasons, and the frequency and intensity of extreme events, can have profound effects on the environment and are changing so rapidly that some species can neither move nor adapt fast enough. Species at risk include mountain species such as pikas and endemic Hawaiian silverswords, which are restricted to cool temperatures at high altitudes, and polar bears which depend on the decreasing sea ice to facilitate their hunting of seals.

- ***Abrupt changes of unknown probability***
  - *Destabilization of the West Antarctic Ice Sheet:* Glaciers whose bases are well below sea level, which includes most of West Antarctica and smaller parts of East Antarctica and Greenland, are sensitive to warming oceans and rising sea levels. Warming oceans erode the bases of glaciers. Rising sea level float the ice, further destabilizing them. Because large uncertainties remain in understanding the physical processes governing glacier destabilization, the probability of an abrupt change in West Antarctic Ice Sheet stabilization occurring in this century is unknown, although it is likely low.
- ***Abrupt changes unlikely to occur this century***
  - *Disruption to the Atlantic Meridional Overturning Circulation (AMOC):* The AMOC is an ocean circulation pattern in which warm near-surface waters flow north into the northern North Atlantic and Nordic Seas, and the cold dense waters of that region flow southward. The AMOC has abruptly shut down and restarted in the past, raising concerns about future abrupt changes. Recent climate and Earth system model simulations indicate that the AMOC is currently stable in the face of likely perturbations, and that an abrupt change will not occur in this century. This is a robust result across many different models.
  - *Potential abrupt changes due to high-latitude methane:* Arctic carbon stores may play a significant role in a century-scale buildup of carbon dioxide and methane (also a greenhouse gas) in the atmosphere, but are unlikely to do so this century. Basic research is needed to assess the long-term stability of currently frozen Arctic and sub-Arctic soil stocks. Research is also needed to address a possible increase in the release of methane gas bubbles from currently frozen marine and terrestrial sediments as temperatures rise.
- ***Additional abrupt changes***
  - The state of knowledge on potential candidate processes that may undergo abrupt change is discussed in this report. Such processes include abrupt climate changes in the physical climate system and abrupt climate impacts of ongoing changes that, when certain thresholds are crossed, can cause abrupt impacts for society and ecosystems. Examples of these processes are: sea level rise due to thermal expansion or ice sheet melting, decreased ocean oxygen, changes to patterns of climate variability, changes in heat waves and extreme precipitation events, disappearance of winter Arctic sea ice, and

rapid state changes in ecosystems, species range shifts, and species boundary changes.

A Review of the Draft 2013 National Climate Assessment. Panel to review the NCA. National Research Council. 2013. National Academies Press. Washington, D.C. http://www.nap.edu/openbook.php?record_id=18322

The Global Change Research Act (GCRA) mandates that a National Climate Assessment (NCA) be produced every four years to inform the President, Congress and the American people about the current state of scientific knowledge of climate change effects on U.S. regions and key sectors now and in the coming decades. The 2013 draft NCA was ambitious in terms of the scope of topics addressed and the extent of public engagement processes involved. New topic areas included the articulation of needs for future research and a vision for an ongoing assessment process; the outreach efforts to help stakeholders define their climate-related information needs; and the initial effort to assess the current state of nationwide climate change response activities.

This document contains an evaluation of the draft 2013 NCA report (see technical inputs to report in summary above) by an expert panel convened by the National Research Council (NRC). The review panel was specifically asked to consider the following Task Statement questions:

1. Is the report responsive to the nation's needs for information on climate variability and change in a global change context, their potential implications, and the potential effects of different response options?
2. Are the key messages and graphics clear and appropriate from a communications perspective?
3. Are there any critical content areas missing from the report?
4. Are the findings documented in a consistent, transparent and credible way?
5. Does the research needs chapter address the most important gaps in existing knowledge?
6. Does the sustained assessment chapter provide an appropriate path to support the development of a sustained assessment process that engages regional and sectoral communities of interest?

The report provides the Panel's consensus responses to the questions listed above. Comments and suggestions focused on specific chapters, statements, and figures are compiled as Appendix A of the report. The Panel focused primarily on offering practical suggestions that could be addressed in the short time that the NCA authors will have to revise the document. Some suggestions will likely need to be viewed as longer-term advice that may be applied in future NCA assessments. Among the Panel's suggested improvements to the draft report include the need to:

- provide a clear overarching framework for the report that (i) helps readers understand climate change as part of a complex system with interacting physical,

biological, and human social/economic dimensions, and (ii) offers practical guidance on using iterative risk management strategies to make decisions in the face of large uncertainties;

- clearly acknowledge how climate change affects and is affected by other types of major global environmental changes and other societal developments;

- offer an explicit discussion about the uncertainties associated with the regional model projections presented in the NCA draft and;

- take full advantage of the e-book format planned for this document through strategic use of hyperlinks among different parts of the report and other innovative approaches that help guide the experience of the NCA's diverse audiences.

Climate change impacts in the United States. Third National Climate Assessment: 2014 report. U.S Global Change Research Program.
http://nca2014.globalchange.gov/report

The NCA report, released in May 2014, was a key deliverable of the President's Climate Action Plan. It is the most comprehensive and authoritative scientific report ever generated about climate changes occurring now in the United States and further changes expected throughout this century. The NCA is the result of a three-year analytical effort of over 300 climate scientists and experts, informed by more than 70 technical workshops and stakeholder listening sessions held across the country. It communicates the impacts of climate change according to geographic region, and by economic and societal sector. These regional findings help translate scientific insights into practical, usable knowledge that can help decision-makers and citizens anticipate and prepare for specific climate-change impacts.

The report includes analyses of impacts on seven sectors—human health, water, energy, transportation, agriculture, forests and ecosystems—in eight geographic regions as well as the coastal areas and oceans. A new, important advance in this assessment is the inclusion of "sectoral cross-cuts" in recognition that multiple impacts are occurring at the same time. The 2014 report also includes the following new chapters: Water, *energy, and land use*; *Urban systems*, *infrastructure, and vulnerability*; *Forestry*; *Tribal, indigenous, and native lands and resources*; *Land use and land cover change*; *Rural communities*; *Biogeochemical cycles*; *Oceans and marine resources; Coastal zone development and ecosystems; Decision support; Mitigation; Adaptation*; and *Research agenda for climate change science*.

Notable findings from the NCA presented in the Overview report include:

1. Climate is changing across the U.S. in a wide range of observations. The warming of the past 50 years is primarily due to human activities, predominantly the burning of fossil fuels.

2. Some extreme weather and climate events have increased in recent decades, and new and stronger evidence confirms that some of these increases are related to human activities.
3. Climate change threatens human health and well-being in many ways, including through more extreme weather events and wildfire, decreased air quality, and diseases transmitted by insects, food and water.
4. Infrastructure is being damaged by sea level rise, heavy downpours and extreme heat; damages are projected to increase with continued climate change.
5. Water quality and supply are jeopardized by climate change in ways that affect ecosystems and livelihoods.
6. Climate disruptions to agriculture have been increasing and are projected to become more severe over this century.
7. Ecosystems are being affected by climate change and their capacity to buffer the impacts of extreme events like fires, floods and severe storms is being overwhelmed.
8. Ocean waters are becoming warmer and more acidic, broadly affecting ocean circulation, chemistry, ecosystems, and marine life.
9. Planning for adaptation and mitigation is becoming more widespread, but current implementation efforts are insufficient to avoid increasingly negative social, environmental and economic consequences.

Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., et al. (eds.) (2013). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.
https://www.ipcc.ch/report/ar5/wg1/

The Working Group I contribution to the IPCC's Fifth Assessment Report (AR5) assesses the current state of the physical sciences with respect to climate change. It considers new evidence of climate change based on many independent scientific analyses from observations of the climate system, paleoclimate archives, theoretical studies of climate processes and simulations using climate models. Key findings of the assessment are accompanied by a description of the degree of certainty reflecting the author team's evaluations of underlying scientific understanding, expressed as a qualitative level of confidence (from very low to very high) and, where possible, a quantified likelihood (from exceptionally unlikely to virtually certain). A *Summary for Policymakers* and a *Technical Summary* accompany the full report, described below.

Among the chapters of the extensive report are those that discuss:

- an introduction to the science presented in the assessment, including concepts and definitions, key indicators for a changing climate (and how current knowledge of these compares with projections made in previous assessments), new scenarios for projected human-related emissions, and the directions and capabilities of current climate science

- variability and change in climate system components from instrumental records (spanning daily to decades-long timescales) and climate archives (spanning many millennia)
- the carbon cycle and its interaction with other biogeochemical cycles, cloud and aerosol interactions and chemistry, the role of water vapor, and feedbacks on the climate system
- natural and anthropogenic drivers of climate change and their metrics, climate models used in simulating past and present climate change, and detection and attribution of changes on global to regional scales
- projections of future climate change derived from climate models, and a discussion of questions relating to the predictability of climate, long term climate change, climate change commitments, and inertia in the climate system
- sea level change and climate phenomena across regions, including the most important modes of variability in the climate system, extreme events, and interconnections between climate phenomena

Key findings include:

Observed Changes in the Climate System

Observations are based on direct measurements and remote sensing, with a diverse, comprehensive set of observations for the period 1950 onwards. Modern observations and paleoclimate reconstructions extending back hundreds to millions of years provide a comprehensive view of climate variability and long-term changes.

- Warming of the climate system is unequivocal, with many of the observed changes since the 1950s unprecedented over decades to millennia.
- Each of the last three decades has been warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, 1983-2012 was likely the warmest 30-year period of the last 1400 years.
- Ocean warming accounts for more than 90% of the increase in energy stored in the climate system between 1971 and 2010. The upper ocean warmed from 1971 to 2010, and likely warmed from the 1870s to 1971.
- Over the last two decades, the Greenland and Antarctic ice sheets have lost mass, glaciers have shrunk almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover decreased in extent.
- From 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] meters. The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia.
- Atmospheric concentrations of CO_2, methane, and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. CO_2 concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and secondarily from net land use change emissions. About 30% of the emitted anthropogenic CO_2 is absorbed by the ocean, causing ocean acidification.

Drivers of Climate Change:

Natural and anthropogenic substances and processes that alter the Earth's energy budget are drivers of climate change. Radiative forcing is the amount of change in energy fluxes caused by these climate drivers.

- Total radiative forcing has led to an uptake of energy by the climate system. The largest contribution is caused by the increase in the atmospheric concentration of CO_2 since 1750.

Understanding the Climate System and its Recent Changes:

Observations, studies of feedback processes, and model simulations are necessary to understand changes in the climate system. An improved set of observations and climate models better enables attribution to changes in climate system components.

- Human influence on the climate system is evident in the increasing greenhouse gas concentrations, positive radiative forcing, and observed warming.
- Improved climate models reproduce continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and cooling following large volcanic eruptions.
- Evidence for human influence on climate system components has grown since the previous assessment, to the point that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century.

Future Global and Regional Climate Change:

Under the new set of scenarios—called Representative Concentration Pathways (RCPs)—atmospheric CO_2 concentrations are higher in 2100 relative to present day as a result of a further increase of cumulative emissions of CO_2 during the 21st century. Climate models of varying complexity are used to generate projections under using these scenarios.

- All except one scenario (with the lowest radiative forcing) project that warming will continue beyond 2100, and global surface temperature for the end of the 21st century is likely to be more than 1.5°C higher than that of 1850-1900. Warming will continue to exhibit variability and will not be regionally uniform.
- Over the 21st century, the contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, with possible regional exceptions.
- Global ocean temperatures will continue to increase during the 21st century, affecting ocean circulation.
- It is very likely that the Arctic sea ice cover will continue to shrink and thin, the Northern Hemisphere spring snow cover will decrease, and global glacier volume will further decrease during the 21st century.
- Global mean sea level will continue to rise during the 21st century. The rate of sea level rise will very likely exceed that observed during 1971 to 2010 due to increased ocean warming and loss of mass from glaciers and ice sheets.
- Climate change will exacerbate the increase of CO_2 in the atmosphere, and further uptake of carbon by the ocean will increase ocean acidification.
- Most aspects of climate change will persist for many centuries even if emissions are stopped.

The report emphasizes that the processes affecting climate can exhibit considerable natural variability. However, recent advances in observations, analyses, and modeling studies have strengthened the evidence linking human activities to ongoing climate change. As models become more advanced, IPCC projections of future climate change have become more detailed. The IPCC process aims to assess the literature as it stands and attempts to reflect the level of reasonable scientific consensus as well as disagreement.

Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (2014) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Part A: http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-PartA_FINAL.pdf
Part B: http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-PartB_FINAL.pdf

Working Group II evaluates how patterns of risks and potential benefits are shifting due to climate change. It considers how impacts and risks related to climate change can be reduced and managed through adaptation and mitigation. The report assesses needs, options, opportunities, constraints, resilience, and other aspects associated with adaptation. This contribution to the Fifth Assessment Report (AR5) assesses a substantially larger knowledge base of relevant scientific, technical, and socioeconomic literature compared to past Working Group II reports.

The report is published in two parts. Part A covers global-scale global-scale assessments of impacts, risks, and adaptation options for economic sectors, human activities, and natural ecosystems. Part B considers the same topics, but from a regional perspective, exploring the issues that arise from the juxtaposition of climate change, environment, and available resources. The Summary for Policymakers for Working Group II can be accessed at:
http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf

Highlighted below are key summary points for Part A:

- In recent decades, changes in climate have caused impacts on natural and human systems globally. In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality.
- Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change. While only a few recent species extinctions have been attributed as yet to climate change, natural global climate change at rates slower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions over the past millions of years.
- Based on studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts. Since the prior assessment (AR4), several periods of rapid food and cereal price

increases following climate extremes in key producing regions indicate a sensitivity of current markets to climate extremes among other factors.

- Currently the worldwide burden of human health from climate change is relatively small compared with effects of other stressors and is not well quantified. There has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming.
- Differences in human vulnerability and exposure arise from non-climatic factors and from inequalities. People who are socially, economically, culturally, politically, institutionally, or otherwise marginalized are especially vulnerable to climate change and also to some adaptation and mitigation responses. Violent conflict increases vulnerability to climate change.
- Impacts from recent climate-related extremes, such as heat waves and droughts, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability. Examples include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure, morbidity and mortality, and consequences for mental health and human well-being.
- Adaptation experience is accumulating across regions in the public and private sector and within communities. Governments at various levels are starting to develop adaptation plans and policies and to integrate climate-change considerations into broader development plans. In North America, governments are engaging in incremental adaptation assessment and planning, particularly at the municipal level. Some proactive adaptation is occurring to protect longer-term investments in energy and public infrastructure.
- Responding to climate-related risks involves decision making in a changing world, with continuing uncertainty about the severity and timing of climate-change impacts and with limits to the effectiveness of adaptation. Uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are large.

Highlighted below are key summary points for the North American region (Chapter 26) in Part B:

- North America's climate has changed, and certain changes attributed to human activity have significant implications for human communities.
- Climate-related changes include an increased occurrence of severe hot weather events, decreases in frost days, and increases in heavy precipitation over much of North America. Earlier peak flow of snowmelt runoff and declines in the amount of water stored in spring snowpack have been observed in the western U.S. and Canada.
- Many climate stresses that carry risks, especially those associated with extreme heat, precipitation, and declining snowpack, will increase in frequency and/or severity in North America in the next decades. Together with climate hazards such as higher sea levels, more intense droughts and increased precipitation variability, these changes are projected to lead to increased stresses to water supply, agriculture, and economic activities.

- North American ecosystems are particularly vulnerable to climate extremes and are under increasing stress from warming temperatures, increasing CO_2 concentrations, and sea level rise.
- Climate stresses occur alongside and can in many cases exacerbate other existing pressures on ecosystems from human activity, such as land use changes and introduction of non-native species.
- Water resources are already stressed in many parts of North America due to non-climate change human activity. They are expected to become further stressed in the face of climate change.
- The 21st century is projected to experience decreases in water quality and increases in urban drainage flooding throughout most of North America as well as a decrease in instream uses such as hydropower in some regions.
- Effects of temperature and climate variability on yields of major crops have been observed.
- Human health impacts from extreme climate events have been observed, although climate-related trends and attribution have not been confirmed to date.
- Observed impacts on livelihoods, economic activities, infrastructure, and access to services in North American urban and rural communities have been attributed to sea level rise, changes in temperature and precipitation, and occurrences of extreme weather events. Differences in severity of climate impacts on human settlements are strongly influenced by social and environmental factors and processes that contribute to risk, vulnerability and adaptive capacity such as populations access to assets, built environmental features and governance.
- Much of the North American infrastructure is vulnerable to extreme weather events. Water resources and transportation infrastructure are in many cases deteriorating and are thus more vulnerable to extremes.
- Adaptation – including technical innovation, institutional strengthening, economic diversification and infrastructure design - can reduce risks in the current climate and manage future risks in the presence of climate change.

Climate Change 2014: Synthesis Report of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (2014) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT.pdf
http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_SPM.pdf

This Synthesis Report is based on the reports of the three Working Groups of the IPCC (including the two reports by Working Group I and II, summarized above), including relevant Special Reports. It provides an integrated view of climate change as the final part of the Fifth Assessment Report (AR5). It is written in a non-technical style suitable for policymakers and addresses a broad range of policy-relevant, but policy-neutral questions. The report consists of two parts: (1) Summary for policymakers and (2) Longer report (see above links).

The report addresses the following topics: observed changes and their causes; future climate change, risks and impacts; future pathways for adaptation, mitigation and sustainable development; and adaptation and mitigation.

In the Synthesis Report, the certainty in key assessment findings is communicated as in the Working Group Reports and Special Reports. It is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence and, when possible, probabilistically with a quantified likelihood.

Drivers of Climate Change

The Earth's climate is influenced by its own internal dynamics and by external factors (referred to as "forcings"), both natural and human-induced. Solar radiation and volcanic eruptions are natural forcings. Emissions of greenhouse gases and aerosols and changes in land use are anthropogenic forcings recognized as drivers of climate change. This chapter summarizes publications on greenhouse gases and aerosols; forests and carbon cycling; ocean acidification; and land use.

Greenhouse gases and aerosols

Greenhouse gases enhance the heat-trapping capacity of the Earth's atmosphere. Globally, human emissions of these gases have been increasing since the Industrial Revolution, primarily from power plant electricity generation and from the combustion of fossil fuels for transportation. The primary greenhouse gases are CO_2, methane, halogenated hydrocarbons, nitrous oxide, and ozone-depleting gases with varying global warming potentials. Human activities also produce aerosols, which can have either a cooling effect by reflecting incoming sunlight away from the Earth (sulfate particles), or a warming effect, by absorbing incoming sunlight and trapping heat in the atmosphere (black soot).

The amount of CO_2 in the atmosphere is controlled by the flow of carbon between the atmosphere, ocean and biosphere. The burning of fossil fuels and changes in landscape have moved carbon from ocean sediments and terrestrial environments and mobilized it into the atmosphere. CO_2 and methane in the atmosphere can change fundamental chemical and physical properties of the atmosphere and oceans. Increasing amounts of CO_2 have dissolved in sea water, making the oceans more acidic. Hence, anthropogenic climate change can be thought of as an enormous perturbation in the global carbon cycle.

Photodegradation leads to increased carbon dioxide losses from terrestrial organic matter. Rutledge S, et al. (2010). *Global Change Biology,* 16:3065-3074. http://dx.doi.org/10.1111/j.1365-2486.2009.02149.x

Photodegradation is the process by which solar irradiance breaks down organic matter (OM), increasing CO_2 fluxes through either photochemical mineralization or microbiological processes. Microbiological decomposition of OM regulated by temperature, moisture, and substrate quality is regarded as one of the dominant processes resulting in CO_2 production in terrestrial ecosystems. Abiotic processes like physical fragmentation by wind and water, leaching and photodegradation can also contribute to decomposition of litter and soil OM. Photodegradation is well known to be

important in cycling of aquatic OM but its relevance in OM cycling in terrestrial ecosystems is poorly understood. Arid and semi-arid ecosystems cover about 30 percent of the Earth's surface and comprise a very large area on a global scale.

This study determined the proportion of the total CO_2 losses caused by photodegradation in two ecosystems: a bare peatland in New Zealand and a seasonally dry grassland in California. During midday on sunny days in summer, when incoming solar irradiance and temperature were highest, the CO_2 efflux due to photodegradation contributed as much as 62 percent and 92 percent of the total half-hourly CO_2 flux from the peatland and grassland, respectively.

The study reported that solar irradiance contributes directly to ecosystem CO_2 losses through photodegradation of OM. Because the ecosystems potentially affected by photodegradation comprise very large areas on a global scale, even small contributions from photodegradation to CO_2 fluxes could represent large fluxes of carbon when summed globally. These losses are currently unaccounted for by carbon cycling models.

Carbon sequestration and greenhouse gas emissions in urban turf. Townsend-Small AC and Czimczik CI (2010). *Geophysical Research Letters*, 37(2):L02707. http://dx.doi.org/10.1029/2009GL041675

Photosynthetic uptake of atmospheric CO_2 can be accompanied by longer-term storage of organic carbon (OC) in undisturbed grassland soil. In turfgrass ecosystems, irrigation and fertilization enhance plant productivity and OC storage. They can also increase soil emissions of other greenhouse gases (GHG) including nitrous oxide (N_2O) (a greenhouse gas ~ 300 times more effective than CO_2). Currently, turfgrass covers 1.9 percent of land in the continental United States.

To better understand the GHG gas balance of urban turf, the authors measured OC sequestration rates and emission of N_2O in ornamental lawns and athletic fields in four parks in Irvine, California. Soil core samples were prepared and tested for total OC and nitrogen contents were quantified with an elemental analyzer (EA) and stocks were calculated using EA data and bulk density. The authors also estimated CO_2 emissions generated by fuel combustion, fertilizer production, and irrigation.

Results from this study show that turf emits significant quantities of N_2O (0.1–0.3 g N m^{-2} yr^{-1}) associated with frequent fertilization in both ornamental and athletic lawns. In ornamental lawns this is offset by OC sequestration (140 g C m^{-2} yr^{-1}), while in athletic fields, there is no OC sequestration because of frequent surface restoration. High OC sequestration rates in some turfs are dwarfed by soil N_2O emissions and CO_2 release during management. OC sequestration by turfgrass would thus not be expected to mitigate GHG emissions in cities. In agricultural soils, fertilizer-derived N_2O emissions can overcompensate for CO_2 uptake by plants and storage in soils, resulting in a positive contribution to global warming. N_2O emissions are too low to overcome the

high rates of OC sequestration in ornamental lawns. A further analysis might consider the impact of lawns on methane balance in cities, as urban lawns have a reduced capacity (13–50 percent) to absorb atmospheric methane compared to native soils.

N_2O emissions from lawns were found to be within the range for agricultural soils, so regional N_2O budgets should not ignore urban soils. The authors noted that future analyses of biological carbon sinks must include a full accounting of GHG gas emissions including N_2O.

Carbon accumulation in agricultural soils after afforestation: A meta-analysis.
Lagniere J, et al. (2010). *Global Change Biology*, 16(1):439-453.
http://dx.doi.org/10.1111/j.1365-2486.2009.01930.x

Afforestation has been cited as an effective method for reducing the atmospheric greenhouse gas CO_2 concentration as a result of the sequestration of carbon (C) in vegetation and soil. Historically, terrestrial C pools and soil organic carbon (SOC) have declined significantly due to land use changes and in particular due to deforestation, i.e., the conversion of forest environments to agricultural land. It is estimated that the forest biomass contains more than 80 percent of all global C contained in the aboveground biomass and that forest soils contain more than 70 percent of the C contained in soils. Understanding the factors that affect the global C cycle is essential to increasing our ability to predict and mitigate the consequences of climate change.

This paper provides a review of the influence of afforestation on SOC stocks based on a meta-analysis of 33 recent publications (totaling 120 sites and 189 observations), with the aim of determining the factors responsible for the restoration of SOC following afforestation. The meta-analysis suggests that it is important to include the organic layer in the accounting. The meta-analysis indicates that the main factors that contribute to restoring SOC stocks after afforestation are: previous land use, tree species planted, soil clay content, pre-planting disturbance and, to a lesser extent, climatic zone. The analysis generated the following findings:

- The positive impact of afforestation on SOC stocks is more pronounced in cropland soils than in pastures or natural grasslands;
- Broadleaf tree species have a greater capacity to accumulate SOC carbon than coniferous species;
- Afforestation using pine species does not result in a net loss of the whole soil-profile C stocks compared with initial values (agricultural soil) when the surface organic layer is included in the accounting;
- Clay-rich soils (>33 percent) have a greater capacity to accumulate SOC than soils with a lower clay content (<33 percent);
- Minimizing pre-planting disturbances may increase the rate at which SOC stocks are replenished.
- Afforestation carried out in the boreal climate zone results in small SOC losses compared with other climate zones, probably because trees grow more slowly under

these conditions, although this does not rule out gains over time after the conversion.

Contributions of stratospheric water vapor to decadal changes in the rate of global warming. Solomon S, et al. (2010). *Science*, 327(5970):1219-1223. http://dx.doi.org/10.1126/science.1182488

Earlier studies have suggested that stratospheric water vapor (SWV) changes might contribute significantly to climate change. This contribution, however, had been difficult to resolve given uncertainties over the magnitude of the radiative effects of water vapor, and the difficulty of ascertaining systematic changes in water vapor measurements due to calibration issues. While tropospheric water vapor—which increases in association with warming—is well simulated in global climate models, key processes that control the distribution and variability of water in the stratosphere are poorly represented. This study evaluates a combination of data and models to determine whether SWV contributed to the flattening of the global warming trend since about 2000.

Data on SWV consists of balloon observations from a single site (Boulder, Colorado) beginning in the 1980s, and high-quality global satellite observations from multiple platforms beginning in the 1990s. These data provide strong evidence for a sharp and persistent drop of about 0.4 parts per million by volume (ppmv) at mid-latitudes after the year 2000. Prior to this decrease, the balloon data suggest a gradual mid-latitude increase in lower SWV of more than 1 ppmv from 1980 to 2000, while certain satellite data sets suggest increases during the 1990s of about 0.5 ppmv. The reduction in SWV remains relatively steady from 2001 through the end of 2007, and the 5-year running mean of the monthly averaged satellite water anomaly is nearly flat from 2001 to late 2009.

Using models to calculate the warming effects of water vapor changes, the authors found that the decrease in water vapor (from seasonally averaged satellite measurements for 1996 to 2000 and for 2001.5 to 2005.5) produced a negative impact (i.e., -0.098 W/m^2 or a cooling effect), while increases (based on an assumption that water vapor increased by 1 ppmv between 1980 and the 1996-2000 period) produced a positive, or warming effect (+0.24 W/m^2). These findings suggest that the decadal changes in SWV vapor have the potential to affect recent climate.

A climate model was used to estimate the effect of the reduced forcing associated with the drop in SWV after 2000 on global average decadal temperature trends. The authors found that this drop decreased the rate of warming compared to what would have been expected for greenhouse gases alone by about 25 percent. When global SWV was assumed to increase (at the upper end of the range suggested by the balloon measurements), the model estimated a steeper rate of global warming from 1990 to 2000 by about 30 percent. Thus, the decline in SWV after 2000 should be expected to have significantly contributed to the flattening of the global warming trend in the past decade, and the increases in stratospheric water may also have acted to steepen the

observed warming trend in the 1990s. It should be noted that additional contributions from other factors (such as solar variations, aerosols, and natural variability) were not considered in this study.

The greenhouse gas value of ecosystems. Anderson-Teixeira KJ and DeLucia E (2011). *Global Change Biology,* 17(1):425-438. http://dx.doi.org/10.1111/j.1365-2486.2010.02220.x

As society faces the urgent need to mitigate climate change, it is increasingly important to understand GHG emissions of terrestrial ecosystems to climate. Ecosystems are valued for their storage of organic matter. Land cover changes may accelerate because of intensifying pressure from agriculture or clearing of original ecosystems and complete displacement of biomes. This typically results in considerable GHG release or long-term changes in GHG flux. Physical characteristics of ecosystems (e.g., snowcover, vegetation) also influence climate change processes. The researchers incorporated the biophysical properties within an ecosystem into a single metric that can be used to design land-use policies that mitigate climate change.

The metric “greenhouse gas value” (GHGV) quantifies the value of maintaining an ecosystem over a multiple-year time frame. The GHGV incorporates changes in ecosystem-atmosphere GHG exchanges that would occur if the ecosystem were to be cleared. The ecosystem’s GHGV is defined as the total benefit of avoiding radiative forcing from GHGs through maintenance of 1 hectare of the ecosystem. It incorporates potential GHG release upon clearing of stored organic matter, the annual flux of GHG’s from the ecosystem to the atmosphere, and probable GHG exchange resulting from disturbance. The GHGV of a particular site depends on qualities such as the number and size of plants; the ecosystem’s ability to take up or release GHG over time and its vulnerability to natural disturbances (e.g., wildfires). For example, a tropical rainforest has a high GHGV due to climate cooling from transpiration processes. The researchers compiled data to calculate the GHGV of 18 "ecoregions" across North and South America and looked at several types of forest, as well as grassland, tundra, tropical savanna and agricultural crops.

The study found that unmanaged ecosystems generally have high or positive GHGVs, whereas managed ecosystems such as croplands generally have lower or negative GHGVs. The authors showed how GHGV may be used to quantify the full GHG effects of land-use or land-cover change by using rich datasets and rigorous statistics. It is noted that the GHGV does not account for the other services a particular ecosystem might provide, such as flood control or food production. Through comparisons with other major paradigms for valuing the GHG contributions of ecosystems, the authors found that—for many purposes—GHGV is the most appropriate method of quantifying the GHG services of ecosystems.

Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration? Cai W-J (2011). *Annual Review of Marine Science*, 3(1):123-145. http://dx.doi.org/10.1146/annurev-marine-120709-142723

Estuaries are a major boundary in the land-ocean interaction zone where OC and nutrients are being processed, resulting in a high water-to-CO_2 flux. The continental shelves take up CO_2 from the atmosphere, accounting for about 17 percent of open ocean CO_2 uptake. CO_2 release in estuaries is largely supported by microbial incineration of highly productive intertidal marsh biomass. Terrestrial incineration could be defined as the biochemical decomposition of OC matter, for example, by bacteria as opposed to thermal incineration by heat. In this review article, the authors discuss CO_2 fluxes across several boundaries at the land-ocean interface, with a focus on the estuary-marsh interaction. The following points are discussed in the article:

- Estuarine waters are a significant source of CO_2 to the atmosphere, with a global efflux of 0.25 ± 0.25 Pg Cy^{-1} (Petagram carbon per year). Therefore, the entire estuary-marsh system, including vegetation, must be a sink of CO_2. A significant part of the marsh-derived OC would survive the estuarine and nearshore recycling and escape to the outer shelf, slope, and the open ocean for further recycling or burial.
- Terrestrial OC carried by rivers, especially large and fast-transit rivers, escapes estuarine decomposition and contributes to respiration in ocean margins and interiors. The observed contemporary CO_2 uptake in mid-to-high-latitude continental shelves (0.35 Pg Cy^{-1}) is largely driven by increases in atmospheric CO_2 concentration. This change of physical driving force also weakens the CO_2 release from lower-latitude ocean margins (0.10 Pg Cy^{-1}), where most of the riverine OC is delivered and respired. Thus, continental shelves are sites of terrestrial OC degradation/incineration but are a CO_2 sink (0.25 ± 0.25 Pg Cy^{-1}) for the atmosphere.
- Although the importance of CO_2 flux and carbon budget in the land-ocean margin is indisputable and CO_2 fluxes for some coastal water components are relatively well characterized, current knowledge of CO_2 flux in coastal zones is still insufficient to derive precise information for climate change prediction.

Large greenhouse gas emissions from a temperate peatland pasture. Teh YA, et al. (2011). *Ecosystems*, 14(2): 311- 325. http://dx.doi.org/10.1007/s10021-011-9411-4

Agricultural drainage is thought to alter GHG emissions from temperate peatlands (bogs, swamps, moors), with methane (CH_4) emissions reduced in favor of greater CO_2 losses. Peatlands are one of the largest natural sources of atmospheric CH_4, and they also emit significant quantities of nitrous oxide (N_2O). Peatland plants capture CO_2 naturally released from the peat, while waterlogged soil conditions inhibit aerobic decomposition, favoring the accumulation of soil organic matter. Agricultural peatlands may have enhanced nitrogen (N) pools and cycling rates due to fertilization or manure additions. The high global warming potential of the peatland is ultimately driven by emissions of non-CO_2 greenhouse gases.

In this study, the authors report greenhouse gas fluxes (CH_4, CO_2, N_2O) from a drained peatland managed as a pasture in the Sacramento-San Joaquin River Delta, California. The peatland was a net source of CH_4 (25.8 ± 1.4 mg CH_4-C m^{-2} d^{-1}) and N_2O (6.4 ± 0.4 mg N_2O-N m^{-2} d^{-1}). CH_4 fluxes were comparable to those of other managed temperate peatlands, whereas N_2O fluxes were very high, equivalent to fluxes from heavily fertilized agriculture and tropical forests. Ecosystem scale CH_4 fluxes were driven by ''hotspots'' (drainage ditches) that accounted for less than 5 percent of the land area but more than 84 percent of emissions. CH_4 fluxes were unresponsive to seasonal fluctuations in climate and showed minimal temporal variability. N_2O fluxes were more homogeneously distributed throughout the landscape and responded to fluctuations in environmental variables, especially soil moisture. Elevated CH_4 and N_2O fluxes contributed to a high overall ecosystem global warming potential (531 g CO_2-C equivalents m^{-2} y^{-1}), with non-CO_2 trace gas fluxes offsetting the atmospheric ''cooling'' effects of photoassimilation (i.e, biological compounds formed by assimilation using light-dependent reactions).

Data from this study suggest that managed delta peatlands are potentially large regional sources of GHG. Soil respiration in this ecosystem was simultaneously regulated by soil moisture and temperature. Spatial heterogeneity in soil moisture modulates the relative importance of each gas for ecosystem global warming potential.

Greenhouse gas (CO_2, CH_4, H_2O) fluxes from drained and flooded agricultural peatlands in the Sacramento-San Joaquin Delta. Hatala JA, et al. (2012). *Agriculture, Ecosystems & Environment*, 150(0):1-18. http://dx.doi.org/10.1016/j.agee.2012.01.009

The Sacramento-San Joaquin Delta in California was drained and converted to agriculture more than a century ago, reversing the rate of carbon (C) accumulation. Since then, the Sacramento-San Joaquin Delta has experienced extreme rates of soil subsidence (i.e., sinking) from peat oxidation. Decreasing the rate of peat oxidation in the Delta is the key to slowing soil subsidence and turning drained Delta ecosystems from net C sources to sinks. To reverse subsidence and capture C, there is increasing interest in converting drained agricultural land-use types to flooded conditions. Rice agriculture is proposed as a flooded land-use type with CO_2 sequestration potential. To evaluate the impact of drained to flooded land-use change on CO_2, CH_4, and evaporation fluxes, the authors conducted two years of measurements at a conventional drained and grazed degraded peatland and newly converted rice paddy.

This study found that the grazed degraded peatland emitted 175-299 g-$Cm^{-2}yr^{-1}$ as CO_2 and 3.3 g-$Cm^{-2}yr^{-1}$ as CH_4. The rice paddy sequestered 84-283 g-$Cm^{-2}yr^{-1}$ of CO_2 from the atmosphere and released 2.5-6.6 g-$Cm^{-2}yr^{-1}$ as CH_4. The rice paddy evaporated 45-95 percent more water than the grazed degraded peatland. Annual photosynthesis was similar between sites. Flooding at the rice paddy inhibited ecosystem respiration, making it a net CO_2 sink. The rice paddy had lowered rates of soil subsidence due to

oxidation compared with the drained peatland, but did not completely reverse subsidence.

The authors concluded that rice appears to provide a substantial benefit for Delta agricultural sustainability in terms of subsidence reversion and carbon sequestration. The flooded status of the rice paddy also had secondary effects on the greenhouse gas budget through increased CH_4 production and higher rates of evaporation. According to the authors, while increased evaporation might be considered a negative consequence in water-limited California, it does benefit local farmers by reducing costs of pumping water out of the Delta islands which are below sea level.

Airborne observations of methane emissions from rice cultivation in the Sacramento Valley of California. Peischl J et al. (2012). *Journal of Geophysical Research: Atmospheres*, 117(D24): 27. http://dx.doi.org/10.1029/2012JD017994

An inventory of annually averaged CH_4 emissions for California was developed by the California Air Resources Board (ARB). The inventory indicates that rice cultivation accounts for 1.8 percent of California's annually averaged anthropogenic CH_4 emissions. Airborne measurements of CH_4 and CO_2 were taken by plane over rice paddies in the Sacramento Valley in the late spring of 2010 and 2011. CH_4 mixing ratios with CO_2 were higher in the growing season than they were before it.

Previous studies showed that, during the growing season, CH_4 and CO_2 emissions were negatively correlated during the daytime (i.e., CH_4 was emitted while CO_2 was taken up by the rice crop during photosynthesis) and positively correlated at nighttime (i.e, CH_4 was emitted while CO_2 was respired). This research was enlarged by extending the study area to the entire rice growing region of the Sacramento River Valley for three days: two in the spring of 2010 and one in the spring of 2011.

The authors derived daytime emission fluxes of CH_4 between 0.6 and 2.0 percent of the CO_2 taken up by photosynthesis on a per-carbon, or mole-to-mole, basis. The authors also used a mixing model to determine an average CH_4/CO_2 flux ratio of -0.6 percent for one day early in the growing season of 2010.

According to the authors, the CH_4/CO_2 flux ratio estimates from a single rice field in the previous study appear representative of rice fields in the Sacramento Valley, indicating the ARB greenhouse gas inventory emission rate of 2.7×10^{10} g CH_4/year is about three times lower than the range of probable CH_4 emissions ($7.8\text{-}9.3 \times 10^{10}$ g CH_4/year) from rice cultivation derived in this study. The authors attribute this difference to decreased burning of the residual rice crop since 1991, which led to an increase in CH_4 emissions from rice paddies in succeeding years, but which is not accounted for in the ARB inventory.

Regional sources of nitrous oxide over the United States: seasonal variation and spatial distribution. Miller SM et al. (2012). *Journal of Geophysical Research,* 117(6), D06310, doi:10.1029/2011JD016951.
http://onlinelibrary.wiley.com/doi/10.1029/2011JD016951/abstract

Nitrous oxide (N_2O) plays a critical role in both stratospheric ozone depletion and climate change. In the atmosphere, it can react with oxygen atoms and catalyze stratospheric ozone destruction. It is a potent GHG and is now the third most important long-lived anthropogenic GHG in terms of radiative forcing. Anthropogenic sources of N_2O include agriculture and fertilizer; fossil fuel combustion, and biomass burning.

This paper presents detailed spatial and temporal information on the magnitude of N_2O emissions over the central U.S. Data from a network of tall tower measurements in 2004 and 2008 were analyzed using high resolution atmospheric simulations to provide regional-scale emissions estimates in time and space, representing important baseline information for GHG regulation. A particle dispersion model was paired with statistical methods for estimating N_2O emissions.

The results indicate peak N_2O emissions in June with a strong seasonal cycle. The spatial distribution of sources closely mirrors data on fertilizer application with particularly large N_2O sources over the U.S. cornbelt. This method estimates a total annual N_2O budget over the central U.S. of 0.9-1.2 teragrams of nitrogen per year (TgN/yr). By this estimate, the U.S. and Canada account for 12-15 percent of the total global N_2O source or 32-39 percent of the global anthropogenic source as reported by the IPCC in 2007.

The 2010 California research at the nexus of air quality and climate change (CalNex) field study. Ryerson T, et.al. (2013). *Journal of Geophysical Research: Atmospheres,* 118(11):1-37.
http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50331/abstract

The California Research at the Nexus of Air Quality and Climate Change (CalNex) field project was conducted throughout California in May, June, and July of 2010. Key project participants were from the Department of Energy, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, State of California and academia. The study was undertaken to improve scientific knowledge for emissions control strategies to simultaneously address the two interrelated issues of air quality and climate change. The effort included emission inventory assessment, atmospheric transport and dispersion, atmospheric chemical processing, cloud-aerosol interactions and aerosol radiative effects.

The purpose of the CalNex study was to:

- Use ambient data emissions (greenhouse gases, ozone and aerosol precursors) to quantitatively evaluate the accuracy of state and federal emissions inventories.

- Provide a better understanding of the chemical factors shaping ozone formation in California.
- Study the effects of new California air quality regulations governing emissions from oceangoing ships, with potential for impacts with both air quality and climate implications.
- Better understand the sources of secondary organic aerosol (SOA) mass in California by measuring its spatial distribution, chemical composition, radiocarbon content, and observing its association with precursor gases in order to deduce and apportion sources.

The following summarizes the results from the collaborative analysis of the CalNex study:

- Climate relevant findings include: leakage from natural gas infrastructure may account for the excess of observed methane over emission estimates in Los Angeles and methane emissions from rice cultivation appear to be significantly underestimated.
- Air quality relevant findings include: mobile fleet volatile organic compounds significantly declined in 50 years and nitrogen oxide emissions continue to have an impact on ozone in the Los Angeles basin; ammonia emissions from dairy farms appear to be significantly underestimated; and nighttime nitrate chemistry contributes to SOA mass in the San Joaquin Valley.
- Findings simultaneously relevant to climate and air quality include the following: marine vessel emissions changes due to low-sulfur fuel and speed controls result in a net warming effect (due to reductions in the indirect cooling effect of sulfate particles) but have substantial positive impacts on local air quality; there are significant differences in the radiative effects of black carbon between anthropogenic and biomass burning sources.

Spatial distribution of United States household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. Jones C and Kammen D (2013). *Environmental Science and Technology,* 48(2):895-902. http://dx.doi.org/10.1021/es4034364

Households in the U.S. alone are directly or indirectly responsible for about 20 percent of annual global GHG emissions, yet represent only 4.3 percent of total global population. This study poses the question: which municipalities and locations within the U.S. contribute the most to household GHG emissions, and what is the effect of population density and suburbanization on emissions?

Using national household surveys, the investigators developed econometric models of demand for energy, transportation, food, goods, and services that were used to derive average household carbon footprints (HCF) for U.S. zip codes, cities, counties, and metropolitan areas. The study found lower HCF in urban core cities ~40 tonnes of CO_2 equivalent (40tCO2e) and higher carbon footprints in outlying suburbs (~ 50tCO2e) with a range from 25 to 80 tCO2e in the 50 largest metropolitan areas. Population density

exhibited a weak but positive correlation with HCF until a density threshold was met, after which it declined. While population density contributed to low HCF in the central cities of large metropolitan areas, the more extensive suburbanization in these regions was estimated to contribute to an overall net increase in HCF compared to smaller metropolitan areas. The study found that suburbs alone accounted for ~50 percent of total U.S. HCF. Differences in the size, composition, and location of household carbon footprints suggest the need for tailoring of GHG mitigation efforts to different populations. Population-dense municipalities tend to be urban centers with employment, housing, and services closely collocated, reducing travel distances, increasing demand for public transit and with less space for larger homes.

Methane emissions from wetlands: Biogeochemical, microbial, and modeling perspectives from local to global scales. Birdgham SD, et al. (2013). *Global Change Biology,* 19(5):1325-1346.
http://onlinelibrary.wiley.com/doi/10.1111/gcb.12131/abstract

Methane is the second most important anthropogenic GHG, with 25 times the global warming potential of CO_2 over a 100-year period. It makes up about 18 percent of human-induced radiative forcing. Human activities account for 54 to72 percent of the CH_4 emissions. Livestock, biomass burning, landfills and other waste management, fossil fuel production and rice agriculture are the largest anthropogenic sources. Wetlands are the single largest natural source and constitute about a third of total global emissions.

In this review article, the authors estimate CH_4 emissions from wetlands and other freshwater aquatic ecosystems; briefly summarize major biogeophysical controls over CH_4 emissions from wetlands; suggest new frontiers in CH_4 biogeochemistry; examine relationships between methanogen community structure and CH_4 dynamics *in situ*; and review the current generation of CH_4 models. One of the most exciting recent developments in this field is the attempt to integrate the different methodologies and spatial scales of biogeochemistry, molecular microbiology, and modeling. CH_4 emissions can be affected by climate, atmospheric CO_2 concentrations, and deposition of sulfate and nitrogen. Evidence suggests that interannual variations in climate have driven many of the observed variations in global atmospheric CH_4 concentrations during the last several decades. Hence, CH_4 from wetlands will likely respond to anthropogenic driven climate change in the future.

Accurate estimates of global CH_4 emissions from wetlands are limited by a lack of robust estimates of the global area and distribution of wetlands. Most estimates do not account for the seasonality of wetland inundation, or do not include small lakes. Estimated global emissions range from 80 to 280 teragram (Tg) per year (1 Tg = 10^{12} g), with a median of 164 Tg per year.

There is evidence that CH_4 emissions from wetlands will provide a strong feedback response to future anthropogenic climate change. While tropical wetlands, which

occupy a larger area and emit higher CH_4 fluxes per unit area, are the source of 47 to 89 percent of global wetland emissions, northern wetlands may disproportionately increase CH_4 emissions in the future for two reasons: (1) northern peatlands and northern permafrost regions store significant amounts of carbon, the latter containing 50 percent of the terrestrial soil carbon pool; and (2) the largest temperature increases are predicted to occur at the higher northern latitudes in the next century. Variability in CH_4 emissions appears to be driven by inundation in the tropics, and by temperature in the boreal region. Modeling studies suggest a link between wetland emissions and the El Niño-Southern Oscillation cycle.

CH_4 cycling in wetlands is regulated by a complex set of microbial, plant, and physicochemical controls. Emissions are the net result of CH_4 production and oxidation. Large scale characteristics, most importantly climatic zone, permafrost, salinity influence, and the presence of peat or mineral soil, control plant composition, hydrology and the soil characteristics that drive anaerobic carbon cycling and CH_4 dynamics. The authors noted that substantial advancements have been made in understanding the biogeochemical controls of CH_4 dynamics and in modeling these, yet significant gaps in knowledge still remain.

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. Disturbance such as stand-replacing fire can release large amounts of CO_2 from forests but forest carbon stocks will usually fully recover over the life cycle of the forest. Humans affect forest carbon dynamics indirectly by altering disturbance regimes, increasing atmospheric CO_2 and nitrogen deposition, and changing global and regional climate.

Longer growing seasons lead to less carbon sequestration by a subalpine forest. Hu J, et al. (2010). *Global Change Biology*, 16(2):771-783. http://dx.doi.org/10.1111/j.1365-2486.2009.01967.x

As global temperatures increase due to climate change, a longer growing season will bolster net ecosystem productivity (NEP), or carbon uptake. This has been proposed as a mechanism to reduce the rate of further warming. Terrestrial and ocean systems absorb approximately half of the anthropogenic CO_2 emitted, but the strength and longevity of these natural carbon sinks may be diminishing. Studies of broadleaf and boreal deciduous forests support this hypothesis, yet subalpine forests with conifer forests may exhibit different ecosystem productivity mechanisms. Winter precipitation controls NEP in Western U.S. mountain ecosystems, where approximately 70 percent of the carbon sink occurs at elevations above 750 meters. For example, high rates of carbon uptake occur in the Sierra Nevada and Rocky Mountains during years of high winter precipitation but primary productivity decreases during years of drought. Years

with a longer growing season length (GSL) were correlated with more rain and shallower snow pack thus less snowmelt runoff during the summer months.

A nine year record (1999-2007) at a Colorado Rocky Mountains subalpine forest study site shows that longer GSL actually resulted in less annual CO_2 uptake. The site receives about 800 millimeters of precipitation annually, with 60 percent as snow and 40 percent as rain. The study analyzed NEP, cumulative snow water equivalent, growing season length, average temperatures during and surrounding winter, evapotranspiration, xylem water content, snow pack content, and soil water content. The precipitation pattern varied significantly from year to year, but interannual temperatures did not.

The study found a significant negative correlation between GSL length and NEP, indicating the longest growing seasons were correlated with the lowest annual rates of forest CO_2 uptake. The three dominant tree species, which have ranges including the Sierra Nevada and areas of the Pacific Northwest, rely heavily on snowmelt late into the growing season. Earlier spring warming and reduced winter snow pack, both of which occur with longer growing seasons, are associated with a reduction in subalpine forest carbon sequestration. The study supports the conclusion that climate change in the Western U.S. is likely to further reduce snow packs, and it is unlikely that increases in summer precipitation will offset the decrease in carbon uptake resulting from reduced snow fall.

Effects of biological invasions on forest carbon sequestration. Peltzer DA, et al. (2010). *Global Change Biology,* 16(2):732-746.
http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2009.02038.x/abstract

Invasive species alter a range of ecosystem processes, including those that affect carbon sequestration. This review article examines the evidence for the direct and indirect impacts of biological invaders on forest carbon stocks. The authors present case studies highlighting a range of invader impacts on carbon sequestration in forest ecosystems, drawing on examples that involve invasive primary producers, decomposers, herbivores, plant pathogens, mutualists, and predators.

Carbon sequestration is the difference between carbon input (gross primary productivity) and carbon loss (respiration, leaching, and disturbances such as from fires). Invasive species that alter carbon fixation, consumption and respiration directly influence the balance between inputs and outputs. Invasions can also lead to indirect effects resulting from predation or compositional changes in the dominant tree species. Functional traits can be used to predict the effects of invaders based on their trophic position, for example:

- ***Primary producers***. Non-native plants are widely thought to be more productive than native species. Litter from invaders is often more decomposable, potentially resulting in higher nutrient availability and primary production, as well as more rapid loss of organic matter. Invasive plants can alter disturbance regimes (for

example increasing fire frequency or intensity), resulting in changes in tree population size structures.

- ***Detritivores and decomposers***. The activities of the soil microbial community and soil invertebrates affect carbon and nutrient levels. For example, burrowing and casting by earthworms process litter and redistribute organic matter, altering soil structure and processes—changes that may favor the growth of faster-growing fungi and bacteria, more rapid turnover of microbial tissue and soil organic matter. Invasive earthworms are well known to increase rates of nutrient cycling and depress the abundance and diversity of microarthropods.

- ***Mammalian herbivores***. Introduced mammalian herbivores (such as beavers, possums, and deer) can affect the recruitment, growth and mortality of trees, leading to structural and compositional changes in forest ecosystems. Their impacts on carbon sequestration will depend upon the stage of forest development, soil fertility and functional traits of the dominant tree species.

- ***Insect herbivores and plant pathogens***. Insects and plant diseases target the primary producers, hence directly affecting carbon sequestration. They also exert long-term indirect impacts by altering nutrient cycling, plant phenology and species composition.

A synthesis of current knowledge on forests and carbon storage in the United States. McKinley DC, et al. (2011). *Ecological Applications,* 21(6):1902-1924. http://dx.doi.org/10.1890/10-0697.1

This review article synthesizes the literature relating to the role of forests in carbon storage, with a focus on the U.S. Among the topics examined is how human activities have influenced forest carbon cycles. The major strategies discussed for protecting forest carbon storage are land use, forest management and fuel treatments, biomass energy, wood products, and urban forest management.

Since forests are a large and active portion of the terrestrial carbon stocks and flows, human activities to maintain forest carbon stocks and promote greater CO_2 uptake and storage have received attention as a means of mitigating or reducing atmospheric CO_2 concentrations. Altered disturbance regimes (such as wildfires), increased atmospheric CO_2 and nitrogen deposition, and changes in global and regional climate are examples of human influences that can affect forest carbon dynamics. In addition to their role in the carbon cycle, forests exert biophysical effects on climate. Forests generally absorb more solar radiation (i.e., they have lower albedo) than other land cover (thus resulting in warming air masses). They support high rates of evapotranspiration (thus increasing evaporative cooling, cloud formation and precipitation). The effects of albedo and evapotranspiration rates are generally less than the carbon effects of land use change.

Of the changes in global land use between 1850 and 1998, global deforestation contributed the most to the amount of carbon released to the atmosphere. Forests are a strong carbon sink; development and conversion of forest to pasture or agricultural land are responsible for much of the current and expected loss of U.S. forests. Harvesting of wood for fuel and timber and clearing of forests for agriculture, pasture and development from 1700 to 1935 have resulted in a loss of approximately 60 percent of the total U.S. forest carbon stocks. Forest regrowth since 1935 has recovered about 40 percent of the carbon lost to the atmosphere. Currently, U.S. forests and forest products store the equivalent of 10 to 20 percent of U.S. fossil fuel emissions.

The authors discuss several strategies for increasing forest carbon, which are summarized below:

- **Avoiding deforestation**. Deforestation results in the gross loss of nearly 90,000 square kilometers of all forest area globally, which is estimated to release 1400-2000 teragram carbon per year. The U.S. gross deforestation rate between 2000 and 2005 was approximately 600,000 hectares (ha)/year, but this was accompanied by a net increase of approximately 400,000 ha/year of land reverted to forests.

- **Afforestation** (the establishment or planning of forests in areas where there have not been forests or where forests have not been present for more than 20 years). The greatest gains in carbon storage will involve afforestation with the least human input (irrigation and fertilization), likely where productive forestland once existed—areas where climatic and soil conditions favor forest growth.

- **Forest management**. Carbon storage is increased when forest growth is increased, when the interval between harvests is increased, or when harvest intensity is decreased. Practices that increase forest growth include fertilization, irrigation, switch to fast-growing planting stock, and weed, disease and insect control.

- **Using wood products to reduce emissions from fossil fuels and store carbon.** Substituting wood biomass in place of fossil fuels can lower atmospheric carbon over time.

- **Carbon in forest products**. Wood and paper continue to store carbon when in use and in landfills. 77 percent of the carbon in wood products and 44 percent in paper products will remain in landfills for a very long time. Using wood as a substitute for steel and concrete lowers fossil fuel emissions because the energy needed for production is considerably lower.

- **Urban forestry**. Since urban areas make up only a small fraction of the U.S. landscape and urban forests require intensive management (irrigation and fertilizer use), they have limited potential to store additional carbon.

- **Fuel treatments** and thinning of foliage may reduce the risk of crown fires. Thus, removing some carbon from the forest protects remaining carbon. There is, however, some uncertainty about thinned stands having much higher tree survival and lower carbon losses in a crown fire.

Each of the above strategies has trade-offs and can be affected by systemic factors (including population growth and development), increasing uncertainty and risk. Large effects on other ecosystems or ecosystem services are likely increasing carbon sequestration in forests, increasing the risk and impact of losing some of these carbon stocks to forest fires, insect outbreaks and storms. Further, climate change threatens to amplify risks to forest carbon stocks by increasing the frequency and severity of these disturbances.

The authors also discussed methods used to estimate carbon and current gaps in knowledge, summarized studies estimating the potential for increased forest sector carbon mitigation and their associated costs, and presented points to consider in formulating policies or projects designed to influence forest carbon sequestration.

Short- and long-term effects of fire on carbon in US dry temperate forest systems. Hurteau MD and Brooks ML (2011). *BioScience*, 61(2):139-146. http://www.bioone.org/doi/abs/10.1525/bio.2011.61.2.9

Plants in forests take in CO_2 from the atmosphere which can mitigate the greenhouse effects of climate change. Energy from the sun, nutrients and water from the soil assimilate the carbon into plant tissue. Carbon is stored in plants but is eventually cycled back to the atmosphere as CO_2 as plants decompose through mineralization by bacteria and fungi or a natural disturbance such as fire. This review paper describes the potential short- and long-term effects of fire on above- and belowground carbon stocks in U.S. dry temperate forests. It also examines the trade-offs between forest management approaches focused on maximizing versus stabilizing aboveground carbon stocks.

Fires historically burned with greater frequency and lower severity than they do today. Fire suppression has resulted in increased understory fuel loads and tree density—a change in structure that has caused a shift from low- to high-severity fires. Carbon emissions from fire in the U.S. are equivalent to 4 to 6 percent of annual human-caused carbon emissions but can be larger. For example, carbon emissions from the 2002 Biscuit Fire in Oregon were equivalent to approximately one-third of the fossil fuel-based emissions in the entire state during that year.

Fire can kill plants thus releasing carbon back to the atmosphere and preventing them from sequestering additional carbon over time. Nutrients are released to the soil, increasing vegetation growth. Although recent annual fire emissions are either below or within range of historical emissions of CO_2 in California, they are well below the upper bound. Fire intensity tends to correlate with fire severity and the balance between

carbon assimilation and carbon emissions can become negative making the site a net source of carbon to the atmosphere. According to the authors, over the long term, fire effects on terrestrial carbon stocks are a function of the balance between carbon loss from direct fire emissions and decomposition and carbon gain from vegetation regrowth. Mitigating fire risk in dry temperate forests requires periodic carbon emissions from prescribed burning or allowing natural fires to burn under certain circumstances (i.e., managed fire). Managing these forests in ways that maximize their resilience to fire also provides for a fully functioning ecosystem.

Attributing carbon changes in conterminous United States forests to disturbance and non-disturbance factors from 1901 to 2010. Zhang F, et al. (2012). *Journal of Geophysical Research: Biogeosciences*, 117(G2):G02021. http://dx.doi.org/10.1029/2011JG001930

Forest ecosystems, major contributors to the sink of atmospheric carbon in recent decades, play a vital role in the global carbon cycle. Two sets of mechanisms are thought to be responsible for forest carbon sinks, including (1) forest regrowth due to *disturbances* (harvest, fire, insect attacks) and land use change, and (2) nondisturbances, or growth enhancement due to climate change, CO_2 fertilization and nitrogen (N) deposition. Long-term net carbon uptake by the forests of the conterminous U.S. is primarily attributed to forest regrowth after disturbances and from abandoned agriculture. However, recent climate changes (increasing temperature, droughts) and atmospheric composition changes (N deposition, rising CO_2 concentration) along with increasing wildfires and insect attacks have had significant effects on the U.S. forest carbon cycle.

In this study, disturbance and nondisturbance effects on net carbon changes in U.S. forests from 1901 to 2010 are quantified using forest inventory data, a continental stand age map, and a model driven by forest stand age, climate and atmospheric composition data. Results showed that on average, the carbon sink in the conterminous U.S. forests from 1950 to 2010 was 206 teragrams of carbon per year (Tg C yr^{-1}) with 87 percent of the sink in living biomass. The study also showed diverse regional patterns of carbon sinks related to the importance of driving factors. For example, from 1980–2010 disturbance effects dominated the carbon changes in the South and Rocky Mountain regions but had minor effects compared with non-disturbance effects in the West Coast region.

Results from this study provide insights into the primary causes of the contemporary carbon sink in forests and the future of U.S. net carbon emissions. The study indicates that new technologies for disturbance tracking, improved forest inventories for carbon studies, and more intensive field studies of interactions between disturbance and non-disturbance factors are needed to improve current estimates of carbon dynamics and future projections.

Effects of biotic disturbances on forest carbon cycling in the United States and Canada. Hicke J, et al. (2012). *Global Change Biology,* 18:7-34. http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2486.2011.02543.x/abstract

In addition to anthropogenic emissions of carbon (C) from fossil fuel burning and other activities, exchange of C with the biosphere is crucial for governing the amount of CO_2 in the atmosphere. Forest carbon cycling occurs mainly through the interplay of CO_2 uptake by plants (photosynthesis) and release of C back into the atmosphere via respiration (decomposition). Both of these processes are strongly mediated by abiotic and biotic disturbance processes.

Insects and pathogens are major disturbance agents that have affected millions of hectares of forests in North America in recent decades. Examples of insects include bark beetles, forest tent caterpillar, gypsy moth, and budworms; plant diseases include fungi, viruses, nematodes, and parasitic plants. Large areas of tree mortality or reduced tree growth resulting from major epidemics imply substantial impacts to the North American carbon cycle. A warming climate is an important driver of insect and disease outbreaks through direct impacts on the disturbance agent as well as increasing the susceptibility of potential host trees in times of drought.

In a review of 24 published studies, the authors described the effects of forest insect and disease disturbances on carbon cycling in the U.S. and Canada. Tools used to study carbon cycling included field observations, aerial surveys and satellite remote sensing and simulation models. They focused on major biotic disturbance events, which are defined as large (>100 km^2) areas of forest affected by insects or disease over time scales less than a decade. The authors identified gaps in knowledge and described available tools for closing these gaps.

Anthropogenic emissions of greenhouse gases have resulted in a warming climate that has facilitated insect and disease outbreaks in recent decades. Changes in both temperature and moisture (drought) have been associated with insect and pathogen outbreaks. The authors conclude that biotic disturbances can have major impacts on forest C stocks and fluxes and can be large enough to affect regional C cycling. However, the authors note that additional research is needed to reduce the uncertainties associated with quantifying biotic disturbance effects on the North American C budget.

Wildland fire emissions, carbon, and climate: Wildfire-climate interactions. Liu Y, et al. (2013). *Forest Ecology and Management,* 317:80-96. http://dx.doi.org/10.1016/j.foreco.2013.02.020

Wildfires have increased in many regions of the globe under a warming and drying trend due to the greenhouse effect. While research has historically focused on fire-weather interactions, there is increasing attention paid to fire-climate interactions. Fire climate looks at the statistics of weather over a certain period and sets atmospheric conditions

for fire activity in longer time frames and larger geographic scales. This paper synthesizes studies on fire-climate interactions and focuses on radiative forcing and climatic impacts of smoke emissions and future fire trends.

Increased fire activity is not simply an outcome of the changing climate, but also a participant in the change. Wildfires impact atmospheric conditions through emissions of gases, particles, water and heat. Emission components with significant atmospheric effects include CO_2 and organic and elemental black carbon. These particles can generate radiative forcing mainly through scattering and absorbing solar radiation and modifying the cloud droplet concentrations hence the cloud radiative properties. The change in radiation can cause further changes in global temperatures and precipitation.

Major findings of the paper include:

- Emissions from wildfires can have significant impacts on radiative forcing. CO_2 emissions can contribute substantially to the global greenhouse effect, and smoke particles reduce overall solar radiation absorbed by the earth-atmosphere, reducing surface temperatures. Smoke particles can suppress cloud formation and precipitation, hence fire may enhance climate anomalies such as droughts.
- Black carbon plays different roles in affecting climate. It could lead warming in the middle and lower atmosphere, and could accelerate snow melting.
- ENSO (El Niño–Southern Oscillation) and various teleconnection patterns influences interannual variability in area burned. Existing climate models have limited capability to provide information on potential changes in ENSO variability and its interaction with other teleconnections, thus precluding projections regarding future shifts in fire potential.
- Fire potential levels in the Southwest are likely to increase during summer and fall, and burned areas in the western U.S. could increase by more than 50 percent by the middle of this century.

The authors conclude by stating that future studies should generate a global picture of all aspects of radiative forcing by smoke particles. Better knowledge is needed of variability of smoke particles; optical properties; plume profiles; locations of warming layers; clouds and smoke; and black carbon roles with organic carbon.

Ocean acidification

Covering most of the Earth's surface, oceans are a vast reservoir for CO_2. Oceans absorb nearly one quarter of the CO_2 released into the atmosphere by human activities every year. As atmospheric levels of CO_2 increase, so do the levels in the ocean, changing the chemistry of seawater–a process called acidification. The ocean's role as a sink for CO_2 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.

Estimation of anthropogenic CO_2 in the ocean. Sabine SL and Tanhua T (2010). *Annual Review of Marine Science*, 2:175-198. http://dx.doi.org/10.1146/annurev-marine-120308-080947

The world's oceans play an important role in the global carbon cycle as they are a vast reservoir of carbon (90 percent), rapidly exchange carbon with the atmosphere, and take up a substantial portion of anthropogenically released carbon from the atmosphere. The oceans are able to hold much more carbon than other compartments of the natural world because most of the CO_2 that diffuses into the oceans reacts with seawater to form carbonic acid (H_2CO_3) and its dissociation products, bicarbonate (HCO_3^-) and carbonate (CO_3^2) ions. Currently, the rate of ocean carbon storage does not seem to be keeping pace with the rate of growth in CO_2 emissions.

The oceans' role in the global carbon cycle involves both the rate at which it absorbs anthropogenic CO_2 (C*ant)* from the atmosphere as well as how and where that CO_2 is stored. Uptake is not necessarily the same as C*ant* storage because ocean transport can move carbon that is removed from the atmosphere in one place and store that carbon in another place. This review article addresses C*ant* storage in the ocean interior. Main points from the article are highlighted below:

- Most studies agree that the global ocean inventory of C*ant* was around 120 petagram carbon (Pg C) in the mid-1990s.
- Based on ocean uptake estimates, the global ocean inventory should be increasing by about 2.2 Pg C per year, giving a total inventory of about 135 Pg C in the early 2000s.
- Estimates of decadal scale ocean inventory changes consistently show increases in C*ant* in the water column, but have not been able to confirm or deny a slowdown in the rate of carbon storage. Ocean interior observations, however, remain the best mechanism for verifying the changes in ocean C*ant* inventory.
- It is extremely difficult to predict how the many possible carbon cycle feedbacks will affect ocean carbon storage; modeling and proxy techniques are limited by our current understanding of the ocean carbon cycle.
- It is critically important that we understand how C*ant* is accumulating in the ocean on timescales relevant to human civilization (years to decades). CO_2 emissions are growing at an ever increasing rate, and the momentum of the carbon and climate system is such that decisions made today will still impact the climate for hundreds to thousands of years to come.

History of seawater carbonate chemistry, atmospheric CO_2, and ocean acidification. Zeebe RE (2012). *Annual Review of Earth and Planetary Sciences*, 40(1):141-165. http://dx.doi.org/10.1146/annurev-earth-042711-105521

Future changes in ocean pH due to human activities and the impacts of these changes on marine life are difficult to predict. In this review article, the author examines the geological record for past ocean chemistry changes, ocean acidification events, and evidence of associated biological responses. Analyses of past changes can provide

valuable context for assessing the current human influence on carbon chemistry and help improve predictions of future changes.

The article reviews the dominant processes controlling ocean carbonate chemistry at different timescales. Based on past long-term changes during various geologic eras, the author concludes that comparisons between these past high-CO_2 steady states and the current and near-future changes are not valid. The time scales involved (centuries compared to millions of years), reservoir sizes (a few thousand petagrams (Pg, or 10^{15}g) compared to 10^8 Pg of carbon), and controls on carbonate chemistry are fundamentally different. Finally, past ocean acidification events—that is, those that involve geologically rapid changes of ocean carbonate chemistry on timescales shorter than ~10,000 years—are presented. Among these events, the author considered the Paleocene-Eocene Thermal Maximum (or PETM, ~55 million years ago) to be the closest analog for the future. However, the rate of carbon input from human activities appears to be greater than during the PETM.

The article concludes that the ocean acidification event expected to result from human activities is unprecedented in the geological past.

Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. Duarte CM, et al. (2013). *Estuaries and Coasts*, 36(2): 221-236. http://dx.doi.org/10.1007/s12237-013-9594-3

Anthropogenic emissions of CO_2 are a major driver of long-term pH changes in the open ocean. In coastal waters, however, changes in pH are affected by numerous other dynamic, complex drivers operating at local to regional scales; these drivers are governed by interactions between processes—many of which are influenced by human activities—on land, in the open ocean and in the atmosphere. Compared to other natural and anthropogenic sources of pH variability, emissions of CO_2 from human activities may play a smaller role in coastal waters compared to the open ocean.

The authors reviewed proxy reconstructions of oceanic pH and found levels to be relatively uniform over the past 20 million years, with a narrow range of variability (typically <0.1pH unit interannually). By contrast, pH in surface coastal waters had been highly variable (as much as 1 pH unit in a 24-hour period, and >0.3 pH unit between seasons or decades).

Current trends in the open ocean show a decline by 0.1 pH unit on average since the Industrial Revolution. In coastal waters, pH trends exhibit a variety of patterns, including periods of both increasing and decreasing levels. While the trends in open-ocean pH are consistent with the decline expected due to increasing levels of atmospheric CO_2, long-term trends in coastal pH indicate that anthropogenic emissions are a relatively minor driver, and a much more complex suite of anthropogenic impacts than those in the open ocean are at play. Enhanced primary production or respiration is often the primary driver in many coastal ecosystems, where changes—which could

have been even larger—are buffered by competing watershed processes. Although coastal ecosystems are where some of the organisms most vulnerable to ocean acidification are found, projections of future pH changes in these waters through the twenty-first century are highly uncertain, given the complexity of pH regulation and limitations of current.

Since the evidence suggests that anthropogenic atmospheric CO_2 emissions are only partially responsible for pH changes in coastal waters, the authors propose an alternative, more holistic paradigm that acknowledges the various anthropogenic drivers of pH change. The proposed paradigm accommodates the broad range of mechanisms involved, including changes in land use, nutrient inputs, ecosystem structure and net metabolism, and emissions of gases to the atmosphere. The authors note that management of ecosystem components and watershed processes may help buffer acidification due to anthropogenic CO_2 locally, and help protect vulnerable coastal organisms.

Changes in deep-water CO_2 concentrations over the last several decades determined from discrete *p*CO_2 measurements. Wanninkhof R, et al. (2013). *Deep-Sea Research I,* 74:48-63. http://dx.doi.org/10.1016/j.dsr.2012.12.005

There is increasing evidence of physical changes in the deep ocean (i.e., below 2000 meters) attributed to increasing atmospheric CO_2 levels and associated climate change. Determining if anthropogenic carbon has entered the ocean interior is important because of the large volume of the deep sea, such that even small increases in concentration can have an appreciable effect on the total water column inventory. However, the methods to determine decadal changes in anthropogenic CO_2 in the deep ocean do not lend themselves to assessment of small changes.

The authors estimated the changes in the interior deep-water inorganic content (using a "discrete pCO2" as the parameter) along three transects in the Atlantic and Pacific oceans. Discrete pCO2 is a measurement of the partial pressure of CO_2 from individual subsurface seawater samples made at a fixed temperature of 20 degrees Centigrade [pCO2(20)], and represents the concentration of undissociated CO_2 molecules dissolved in seawater . Because an observed change in pCO2(20) is not by itself a definitive indicator of anthropogenic CO_2, the researchers also measured changes in chlorofluorocarbons (CFCs) to discern whether chemical changes are due to natural or anthropogenic causes. These changes were measured on decadal time scales using observations from the World Ocean Circulation Experiment/World Hydro Program of the 1980s and 1990s and the CLIVAR/CO2 Repeat Hydrography Program of the past decade.

The results indicate that appreciably more anthropogenic carbon is entering the ocean interior than several current observation- and model-based techniques indicate. Patterns in CFCs along with output from an ocean model suggest that the changes in pCO2(20) and dissolved inorganic carbon are of anthropogenic origin. However, the

authors state that the paucity in pCO2(20) data and appreciable uncertainty make the quantification of this signal tentative.

Land use

Human activities can affect regional climate through land use changes, such as deforestation, irrigation, urbanization. Modifications to land surfaces affect the amount of solar radiation that is reflected by such surfaces back into space. For example, there is strong evidence that deforestation increases the reflection of sunlight and impact local air temperature. Urbanization and the use of certain building materials (such as white roofs or dark pavements) reduce or increase the warming associated with "urban heat islands." In addition to affect 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 the Earth's, river runoff and irrigation.

Scaling of the urban heat island effect based on the energy balance: nighttime minimum temperature increase vs. urban area length scale. Lee TW and Ho A (2010). *Climate Research,* 42:209-216. http://dx.doi.org/10.3354/cr00901

Several studies have previously demonstrated that the urban heat island (UHI) effect is associated with urbanization. This study investigates the relationship between the UHI effect and growth in urbanized land surface area in two of the warmest urban areas in the United States: Phoenix and Tucson, Arizona. Phoenix has had a substantial increase in the urbanized land area from 1984 to 1999, growing at an annual rate of 39 square kilometers (km^2) per year, while Tucson's growth has not been as dramatic at 4.7 km^2 per year. Both cities experience similar meteorological conditions, and are similar in terms of city structures (that is, high-rise buildings are small in number and concentration) and materials used in pavements and building facades. Hence, comparing the two urban areas allows the effects of urbanized land area to be isolated.

Satellite image data are used to determine changes in the urbanized land area. Nighttime minimum temperatures—which have been increasing in both cities—are used as an indicator of the UHI effect. The investigators developed a direct relationship between nighttime minimum temperature and the *length scale* of the urbanized area (defined as the square root of the area). This relationship is explained by the effect of increasing urbanized land area on the thermal energy transport of the air mass above these areas, as follows: energy from the sun heats up urban surfaces during the day; at night, the heat from these surfaces forms a high-temperature air mass which needs to be cooled by the surrounding air. The rate of cooling of these surfaces decreases as the length scale of urbanized areas increases, resulting in higher nighttime temperatures. This study thus provides insights on the importance of the length scale of an urbanized area in determining the severity of the UHI effects.

Effects of urban surfaces and white roofs on global and regional climate. Jacobson M and Ten Hoeve J (2011). *Journal of Climate*, 25(3):1028-1044. http://dx.doi.org/10.1175/JCLI-D-11-00032.1

Urban areas are generally warmer than vegetated areas around them. Urban surfaces reduce evapotranspiration and have different heat capacities, thermal conductivities, and albedos (fraction of solar radiation reflected by a surface). The Intergovernmental Program on Climate Change Fourth Assessment Report concluded that the urban heat island effect (UHI) may have increased temperatures about ~ 0.065 Kelvin (K) over land and about ~ 0.022 K globally from 1900-2008. Global heat studies, however, do not distinguish which factors contribute most to temperature changes in urban areas.

White roofs have generally been thought to reduce summer air conditioning energy demand and to change surface albedo. The authors quantified the effects of urban surfaces and white roofs on climate, using a 3D model and input satellite data to estimate the climate response of theoretically converting all roofs within urban areas worldwide to white roofs. This nested modeling technique attempts to simulate climate, weather and air pollution on all scales. The study accounted not only for local impacts of the heat island effect, but also feedbacks of the effect to the global scale.

A conversion of rooftops worldwide to white roofs, accounting for their albedo effect only, was calculated to cool population-weighted global temperatures by ~0.02 K but to warm the Earth overall by ~0.07 K. Local ground cooling stabilized surface air, which reduced heat fluxes and local cloudiness, increased local surface solar radiation, resulting in local cooling. However, although white surfaces are cooler, the increased sunlight they reflect back into the atmosphere can increase absorption of light by dark pollutants such as black carbon, leading to warming. The study did not account for the reduced energy use (and thus reduced emissions) resulting from the cooling effect of white roofs.

Irrigation in California's central valley strengthens the southwestern U. S. water cycle. Lo M and Famiglietti JS (2013). *Geophysical Research Letters,* 40(2):301-306. http://onlinelibrary.wiley.com/doi/10.1002/grl.50108/abstract

This paper examines the impacts of irrigation in California's Central Valley on local and regional climate. Earlier studies have demonstrated that irrigation increases evapotranspiration, which can substantially affect local climate, such as by cooling the land surface. Irrigation also increases soil moisture, which in turn affects precipitation through changes in local evapotranspiration or in water vapor transport. Investigators used a global climate model and realistic estimates of regional agricultural water use to simulate changes in evapotranspiration over a 90-year period (only the last 45 years of the simulations are used in this analysis to reduce uncertainties). Simulations with and without irrigation were compared.

The simulations show that irrigation significantly increases evapotranspiration over the Central Valley during the summer (by 100 percent). Large scale atmospheric circulation patterns transport this additional water vapor to the southwestern United States, increasing precipitation over that area by 10 to 20 percent. Using a model, the investigators demonstrated a mechanism by which the transported water vapor can enhance summer monsoons and accelerates the regional water cycle in the southwest. With the increased precipitation, summer runoff in this region increases by about 56 percent; a 28 percent increase occurs over the Colorado River Basin. According to the authors, this study supports a link between water management practices in one region and changes in climate in another, highlighting the importance of considering human-driven influences on the hydrological cycle and regional climate.

The response of coastal stratocumulus clouds to agricultural irrigation in California. Lo M-H, et al. (2013). *Journal of Geophysical Research: Atmospheres,* 118(12):6044-6051. http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50516/abstract

Studies have demonstrated that irrigation in California's Central Valley produces substantial effects on local climate and the regional hydrological cycle. The Central Valley is a vast agricultural region that extends over 650 km in length and 40-150 km in width, and accounts for one sixth of irrigated land in the United States. Whether Central Valley irrigation affects stratocumulus clouds (SC) on California's coast by modifying local circulation and land surface energy budgets is the question explored in this study.

Climate model simulations were used to evaluate the impacts of irrigation on SC. SC are nonprecipitating or drizzling clouds that cover a large area of the world's oceans. Due to their long lifetimes and high albedos (fraction of solar radiation reflected by a surface), SC have an overall net radiative cooling effect on the Earth's climate. The mechanism of SC formation and maintenance has been well studied; however, relatively few studies have examined changes in SC due to climate change or future changes in a warmer climate, particularly at a regional scale.

The simulations showed that irrigation in the Central Valley tended to decrease SC coverage over the eastern Pacific Ocean in the vicinity of California. The reduced surface temperature over the irrigated area decreases the difference between land and sea temperatures. This causes a weakening of the local circulation (sea breeze) and other changes in the near-coastal region that eventually reduce SC coverage. Simulated absorbed surface solar radiation over this region increased by 3.7 percent, resulting in warmer surface temperatures. Hence, the study found that irrigation causes reductions of the SC, allowing more solar radiation to penetrate the atmosphere and reach the surface, having a net warming effect. There are several large regions with intensive irrigation around the world, such as Peru and China, which may have significant impacts on nearby SC and the radiation budget.

The impact of global land-cover change on the terrestrial water cycle. Sterling SM, et al. (2013). *Nature Climate Change,* 13:385-390.
http://dx.doi.org/10.1038/nclimate1690

Changes in land cover directly affect the timing and magnitude of evapotranspiration (ET), leading to alterations to the water cycle. This study examines the effect of global land-cover changes on terrestrial evapotranspiration (TET). Over 1,500 mean annual ET estimates for discrete land-cover types across the globe, covering the years 1822-2004 (records vary from 1 to 107 years), were used in the analysis.

The investigators estimate that land-cover has affected 41 percent of TET (the term "appropriated" is used to refer to a measure of this amount—that is, the flux or mass touched, but not necessarily quantitatively altered by human activity). Estimated changes are mapped at a fine-scale (5 min) resolution to reveal hotspots of reduced and increased ET across the globe. Land-cover change has reduced global annual average TET by about 5 percent (approximately 3,500 cubic kilometers per year). The largest reductions were associated with wetland loss, and the largest increases with reservoir creation. In addition, the investigators found that the direction of change in the following four surface parameters consistently projected the direction of ET change: available water; available energy; surface roughness; and leaf area index. Where there are differences in direction of change in the four parameters, available water governed the direction of change in ET. While the net result of major anthropogenic drivers is an increase in annual runoff, the relative magnitudes of the impacts of these drivers are similar, uncertain, and in opposite directions (land-cover change and changes to meteorological forcing increased runoff, while the direct effects of CO_2 on plants, decreased runoff).

The study findings illustrate that human activity can exaggerate water resource problems in some areas of the globe, and alleviate them in others. Future land-cover changes in large areas of high ET that are yet relatively untouched can have particularly significant impacts on the water cycle. As noted by the authors, determining where the anthropogenic effects are additive and where they tend to cancel each other will be of critical importance to water planners.

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, often defined as "average weather," is commonly measured in terms of temperature, precipitation, atmospheric pressure, and wind over a period of time (generally 30 years). Long-term changes in these and other parameters are used to track changes in climate. This chapter summarizes publications on: temperature; precipitation; droughts; and extreme events.

Temperature

Warming of the Earth's surface temperatures is the most widely reported direct observation of changes in climate. The global average temperature has increased by more than 1.4 degrees Fahrenheit (^{o}F) over the last century. In California, annual average air temperatures have increased by about 1.5 ^{o}F since 1895; minimum temperatures have increased at a rate almost twice as fast as the increase in maximum temperatures. Among the lines of evidence for a changing climate is the increased frequency of extreme climate events including record high temperatures. Extreme heat events (EHEs) are increasing in frequency in large cities and are responsible for a greater number of climate-related illnesses and deaths. While natural variability continues to play a key role in extreme weather, climate change has shifted the odds and changed the natural limits, making EHEs more frequent and more intense.

Why hasn't the earth warmed as much as expected? Schwartz SE, et al. (2010). *Journal of Climate*, 23 (10):2453-2464. http://dx.doi.org/10.1175/2009JCLI3461.1

One manifestation of the warming of the climate system over the past century has been an increase in global mean surface temperature (GMST), "very likely" due mainly to increased concentrations of long-lived GHGs, according to the IPCC. When compared to best estimates of the increase in GMST expected from increased concentrations of GHGs, the observed increase over the industrial era is about 40 percent lower. This paper presents a systematic examination of the possible reasons for this warming discrepancy.

The authors showed that relatively little of the warming discrepancy can be attributed to a countervailing natural cooling over the time period, or to thermal lag of the climate system response to the increased GHG concentrations. The discrepancy is found to be due mainly to a combination of two factors: the climate sensitivity being too high ("climate sensitivity" is a metric characterizing the response of the global climate system to a given forcing, such as GHGs) and the offsetting forcing by increased concentrations of atmospheric aerosols.

Estimates of climate sensitivity are used to inform decisions and set policy regarding future fossil fuel emissions compatible with any chosen maximum allowable increase in GMST. Hence, improved knowledge of the earth's climate sensitivity is urgently needed. The principal limitation to empirical determination of climate sensitivity or to the evaluation of the performance of climate models is the uncertainty forcing by aerosols.

Addendum.

Comments on "Why hasn't the earth warmed as much as expected?" Knutti R and Plattner G-K (2012). *Journal of Climate*, 25 (6):2192-2199. http://dx.doi.org/10.1175/2011JCLI4038.1

Two conclusions in the Schwartz et al. study are revisited in this commentary. The authors show that 1) in contrast to Schwartz et al., there is no conflict between expected and observed warming, as long as all known forcings and the imbalance of the climate system and their respective uncertainties are properly taken into account; and 2) the calculations by Schwartz et al. are based on erroneous assumptions about the behavior of the carbon cycle and a confusion of the relevant time scales.

Response to Comments on "Why hasn't the earth warmed as much as expected?" Schwartz SE, Charlson RJ, Kahn RA, Ogren JA, and Rodhe H (2012). *Journal of Climate*, 25 (6): 2200-2204. http://dx.doi.org/10.1175/2011JCLI4161.1

Schwartz et al. contend that Knutti and Plattner mischaracterize the "warming discrepancy" presented in their paper, "*Comments on "Why hasn't the earth warmed as much as expected?"* They state that if the causes of the discrepancy "are properly taken into account, there is no discrepancy between predicted and observed warming."

In response, Schwartz et al. note that it is not possible to represent aerosol forcing or total forcing in climate models, given the present uncertainty; this limitation precludes making conclusions, with any degree of confidence, about warming due to incremental amounts of long-lived greenhouse gases (LLGHGs) in the present atmosphere. They maintain that their examination of the possible causes of the warming discrepancy contributes valuable information to understanding the consequences of the increases in atmospheric greenhouse gases over the past 200 years.

Schwartz et al.'s calculations indicated that avoiding exceedances of the target maximum increase in global mean surface temperature would require an abrupt halt to emissions of CO_2 and other LLGHGs. This analysis, according to Knutti and Plattner, did not account for disequilibrium between the current climate and forcing; neither did it consider removal of excess CO_2 following cessation of

emissions and aerosols from the atmosphere by the oceans and the terrestrial biosphere—doing so results in a lower temperature increase relative to preindustrial times (a value of 1.6 K rather than 2.1 K, as obtained by Schwartz et al.). In response, Schwartz et al. question the level of confidence in Knutti and Plattner's model calculations, as they are based on highly uncertain assumptions. They stand by the key conclusions of their paper, and maintain the importance of greatly reducing the uncertainty in aerosol forcing.

Temperature and equivalent temperature over the United States (1979–2005). Fall S, et al. (2010). *International Journal of Climatology*, 30(13):2045-2054. http://dx.doi.org/10.1002/joc.2094

Recent studies have suggested that the use of temperature alone to monitor climate change may not provide a complete evaluation of the heat storage changes to the earth system or of surface air heat content. In this study, temperature and equivalent temperature (T_E, which combines air temperature and humidity in a single variable) trends over the United States from 1979 to 2005 are investigated. Changes in both temperature and moisture are examined at different time scales and pressure levels (at near-surface or 2 meters and at standard pressure levels up to 200 millibars, or mb); in addition, both temperature (T) and T_E are related to vegetation (using the normalized difference vegetation index or NDVI) and to land use/cover.

Decadal trends in both T and T_E show significant warming. The differences in the magnitude of the trends in T and T_E are larger near the surface at 2 m and decrease upward, such that there is very little trend difference at 200 mb. While most (about 90 percent) of the magnitude of T_E is explained by temperature, its moisture component induces larger trends and variability relative to T. Atmospheric near-surface moisture (such as from vegetation transpiration and soil moisture evaporation) strongly influences this moisture component; at the 2 m level, there is a stronger relationship between T_E and moisture compared to T and moisture, but this difference decreases upward, disappearing at 300-200 mb. This study therefore demonstrates that in addition to temperature, atmospheric heat content may help to quantify the differences between surface and tropospheric heating trends, and hence the impact of land cover types on the surface temperature changes.

Results from this study suggest that land cover types influence both moisture availability and temperature in the lower atmosphere and that T_E is larger in areas with higher physical evaporation and transpiration rates. As a result, using T_E to assess tropospheric heating trends is not only an efficient way to investigate the vertical structure of the combined effects of temperature and moisture, but it may also help obtain an improved estimate of the impacts of surface properties on heating trends.

Climatic changes in western North America, 1950-2005. Booth E, et al. (2011). *International Journal of Climatology*, 32(15):2283-2300. http://dx.doi.org/10.1002/joc.3401

This study analyzed historical climate data to determine the extent to which the climatology of western North America (WNA) has been altered over the period 1950-2005. Daily temperature and precipitation data from 490 stations across western Canada and the Western United States were obtained (from the Historical Climatology Network database compiled by the National Climatic Data Center) and analyzed to assess changes in climate. Six geographic regions were studied, with California and Nevada included as one region (CNV). Trends were calculated for eight indicators (e.g., frost days, growing season length, warm days, warm nights, very wet days, total annual precipitation) focusing on station-specific temperature and precipitation thresholds that define regional climatology. Indices were calculated on an annual basis for each station for the period 1950-2005 and for one station in each region for the period 1906-2005.

Overall, temperature indicators showed a general warming trend over the entire study area. Precipitation indicators, although more varied, showed moderately increasing precipitation volume and intensity. For the CNV region, trends indicate increasing daily minimum temperatures and a substantial reduction of frost days. This region showed the greatest amount of warming from 1950-2005. Stations across California showed a slight significant increase in the growing season length, especially in central and northern areas. Increasing maximum temperatures were more spatially varied, with trends most apparent in Southern and Northern California and the Central Valley. The Central Coast area seems to have experienced a slight lowering of maximum temperatures. Precipitation trends over CNV were weaker than in other regions, with a majority of stations reporting no statistically significant trend. The authors note that the substantial warming and lack of increase in precipitation over the CNV region may pose a serious threat to agricultural operations and a burgeoning population.

Modeled large-scale warming impacts on summer California coastal-cooling trends. Lebassi-Habtezion B, et al. (2011). *Journal of Geophysical Research: Atmospheres*, 116(D20):27. http://dx.doi.org/10.1029/2011JD015759

Observational analyses have indicated that cooling of summer (i.e., June to August) maximum temperature (Tmax) values in coastal California over the last several decades could be due to increased irrigation, coastal upwelling, low level cloud cover and/or urban cool-islands. Researchers have shown that this cooling from 1970 to 2005 was due to a “reverse reaction”—the large-scale warming of inland areas, which increases sea breeze activity that overwhelms the warming in low-elevation South Coast Air Basin (SoCAB) coastal areas. This study used a modeling analysis (Regional Atmospheric Modeling System or RAMs mesoscale meteorological model) of SoCAB to quantify local coastal climate change impacts from large-scale warming.

The overall goal of the model simulations of current (i.e., 2001–05) and past (i.e., 1966–70) SoCAB summer sea breeze wind and temperature patterns was to relate their changing patterns to the observed concurrent inland-warming and coastal-cooling patterns. The simulations incorporated the combined effects from large-scale warming and sea surface temperature (SST) changes. Comparison of present- and past-climate simulations showed significant increases in summer daytime sea breeze activity by up to 1.5 meters per second (in the onshore component) and a concurrent coastal cooling of average-daily peak temperatures of up to −1.6^{o} centigrade.

Results from this study support observation that the concurrent coastal cooling is an indirect reverse reaction to the large-scale warming of inland areas. Given this, the authors predict beneficial societal impacts from this reverse-reaction to large-scale warming, including possible decreased ozone levels, less per-capita energy requirements for cooling, and less heat stress on humans.

Surface water vapor pressures and temperature trends in North America during 1948-2010. Isaac V and van Wijngaarden W (2012). *American Meterological Society,* 25:3599-3609. http://dx.doi.org/10.1175/JCLI-D-11-00003.1

It has been suggested that increased water vapor pressure (WVP) may increase precipitation and affect storm intensity. Saturation WVP increases exponentially with temperature. Hence, atmospheric WVP is expected to increase with warming temperatures, assuming relative humidity remains unchanged. Water vapor is itself a greenhouse gas. Over one-quarter billion hourly values of temperatures and relative humidity observed at 309 stations located across North America during 1948-2010 were studied. The data were examined for inhomogeneities (which can occur because of changes in instruments or observation procedure, modification of the station site, and automation), as these could result in substantially larger trends if not accounted for.

WVP and temperature were found to increase at the large majority of the stations located thorough out North America. Large differences in the seasonal and geographic distributions of the temperature and WVP trends were evident.

- Statistically significant warming trends affecting Midwestern United States, Canadian prairies, and the Western Artic are evident in winter and to a lesser extent in spring while significant increases in WVP occur primarily in summer for some stations in the eastern half of the U.S.
- The temperature trends averaged over all stations from 1948-2010 were 0.30, 0.24, 0.13, and 0.11^{o}C per decade in the winter, spring, summer, and autumn seasons, respectively; WVP trends were 0.07, 0.06, 0.11, and 0.07 hecto Pascal (hPa) per decade in the winter, spring, summer, and autumn seasons, respectively.
- The averages of these seasonal trends are 0.20^{o}C per decade and 0.07 hPa per decade, which correspond to a specific humidity increase of 0.04 gram per

kilogram per decade and a relative humidity reduction of 0.5 percent per decade.

Comparing climate projections to observations up to 2011. Rahmstorf S, et al. (2012). *Environmental Research Letters*, 7(4):044035. http://dx.doi.org/10.1088/1748-9326/7/4/044035

Climate change projections are increasingly used in decision-making. It is therefore important to assess how well past projections match observational data. Five years ago, it was found that CO_2 concentration and global temperature during 1990–2006 closely followed the central prediction of the third Intergovernmental Panel on Climate Change (IPCC) assessment report, while sea level was tracking along the upper limit of the uncertainty range. This study presents an update with five additional years of data to better describe the evolution of global-mean temperature and sea level.

Global temperature data for the past few decades were analyzed and compared to projections published in the third (2001) and fourth (2007) assessment IPCC reports. Because the IPCC projections do not attempt to predict the effect of solar variability, volcanic eruptions or El Niño events, the global temperature data were adjusted for these influences on climate. Observational data from 1980 to 2011 were used for comparison to model projections.

The results show that global temperature continues to increase in close agreement with the best estimates of the IPCC, especially if the effects of short-term variability due to the El Niño/Southern Oscillation, volcanic activity and solar variability are considered. The adjusted observed global temperature change closely follows the central IPCC projections. The upper limit of temperature projections from other studies also correspond to the observed warming trend. In addition, these studies correctly predicted that the global warming signal would emerge from the noise of natural variability before the 21st century.

Sea level trend measured by satellites since 1993 has continued unchanged when extending the time series by 5 years. There is a linear trend for the years 1993-2011. This trend runs near the upper limit of the projected uncertainty range mentioned in the third and fourth IPCC assessments. Unlike temperature, the rate of sea-level rise of the past few decades is greater than projected by the IPCC models (60 percent faster than the best IPCC estimate for the same timeframe). This suggests that IPCC sea-level projections for the future may also be biased low.

The IPCC projections assumed that Antarctica will gain enough mass in the future to compensate for mass losses from Greenland. However, observational data have indicated that the ice sheets in Antarctica and Greenland are increasingly losing mass. For this reason, an additional contribution to sea level ('scaled-up ice sheet discharge') was suggested in the IPCC fourth assessment.

The climate velocity of the contiguous United States during the 20th century. Dobrowski SZ, et al. (2013). *Global Change Biology*, 19(1):241-251. http://dx.doi.org/10.1111/gcb.12026

The ecological impact of climate change will depend, among other factors, on whether its rate of change will exceed the rate at which species can adapt or move to suitable environments. The authors assessed the velocity of climate in the contiguous United States during the 20th century (1916-2005). "Climate velocity" describes the rate and direction of change, and is calculated by dividing the rate of climate change through time (for example, ^{o}C per year) by the spatial gradient in climate at that location (for example, ^{o}C per kilometer per year, yielding an estimate velocity and direction of climate displacement across a landscape. The following climate variables were analyzed: minimum temperature, actual evapotranspiration (i.e, the amount of water transferred from land to the atmosphere), and climatic water deficit (a measure of drought stress on soil and plants). These three variables represent important limiting factors that are predictors of plant species occurrence.

The analysis revealed complex spatial and temporal patterns. Velocity vectors varied regionally, showed variable and opposing directions, and shifted direction through time. While the velocities for the two variables characterizing climatic water balance and temperature were similar in magnitude, they frequently differed in direction, showing divergence through time. The complex climate patterns suggest that a more complete understanding of changes in multiple climatic factors (instead of only changes in temperature), may help explain unexpected or conflicting observations of climate-driven range shifts observed during the 20th century.

Recent global-warming hiatus tied to equatorial Pacific surface cooling. Kosaka Y and Xie S-P (2013). *Nature*, 501:403-407. http://dx.doi.org/10.1038/nature12534

Despite the continued increase in atmospheric greenhouse gas concentrations, the annual-mean global temperature has not risen in the twenty-first century, challenging the prevailing view that anthropogenic forcing causes climate warming. Two schools of thought exist regarding the cause of this hiatus in global warming. One suggests a slowdown in radiative forcing due to atmospheric water vapor, the rapid increase of sun-reflecting atmospheric aerosols, and the 2009 *solar minimum* (period of least solar activity in the 11 year solar cycle). The other considers the hiatus to be part of natural variability, especially influenced by a La-Niña-like cooling in the tropical Pacific.

The authors used an advanced climate model that takes radiative forcing and historical tropical Pacific sea SST as inputs, focusing on trends from 2002 to 2012. The simulated global-mean temperature is in excellent agreement with observations, showing that the decadal cooling of the tropical Pacific caused the current hiatus. The authors concluded that the recent cooling of the tropical Pacific and hence the current hiatus are probably due to natural internal variability rather than a forced response. If

so, the hiatus is temporary, and global warming will return when the tropical Pacific swings back to a warm state.

Regional Climate Trends and Scenarios for the U.S. National Climate Assessment Part 5. Climate of the Southwest U.S. Kunkel KE, et al. (2013). National Oceanic and Atmospheric Administration, National Environmental, Satellite, Data, and Information Service. NOAA Technical Report NESDIS 142-5. Washington, D.C**.** http://scenarios.globalchange.gov/sites/default/files/NOAA_NESDIS_Tech_Report_142-5-Climate_of_the_Southwest_U.S_0.pdf

See summary under *Authoritative Reports*, page 28.

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.

In California, statewide and regional trends in total precipitation have shown little change over the past century. Recent studies have examined changes in heavy precipitation patterns, including the nature of "atmospheric rivers," powerful winter systems that draw warm, wet air from the tropics near Hawaii and deliver unusually warm and unusually wet storms on the west coast of North America.

Influence of modes of climate variability on global precipitation extremes. Kenyon J and Hegerl GC (2010). *Journal of Climate*, 23:6248-6262. http://dx.doi.org/10.1175/2010JCLI3617.1

The probability of climate extremes is strongly affected by atmospheric circulation. Variations in global-scale extreme precipitation with circulation have been studied less intensely than changes in mean or total precipitation, and studies usually focus on regions rather than analyzing worldwide data for extremes. This study quantifies the worldwide influence on station-based indices of intense precipitation of three major modes of circulation: the ENSO, the Pacific interdecadal variability as characterized by the North Pacific index (NPI), and the North Atlantic Oscillation (NAO)–Northern Annular Mode. The authors explore how precipitation extremes of different rarities respond to circulation.

Five indices of extreme precipitation for hundreds of stations across the globe were analyzed against the positive and negative phases of large-scale circulation. For example, for the ENSO, the "cold tongue index" obtained from the University of Washington was used. The index is a measure of monthly sea surface temperature anomalies from 1849-2005 in a study region. Station-based indices that determine the daily variability of temperature and precipitation were obtained. Some stations have indices going back to the late nineteenth century; however, coverage is much better during the second half of the twentieth century. Statistical analysis is used to determine if the different phases of a major circulation mode cause a significant difference in the values of the precipitation extremes indices for an individual station.

The authors found significant precipitation responses largely in the same regions as temperature responses, with the exception that precipitation responses do not extend as far into the high latitudes, consistent with earlier observations for total precipitation. There are distinct regional patterns of response to all these modes of climate variability; however, precipitation extremes are most substantially affected by the ENSO, where effects are seen throughout the world. The North Atlantic Oscillation has a strong, continent-wide effect on Eurasia and affects a small percentage of stations across the Northern Hemispheric mid latitudes. The NPI influence on precipitation extremes is similar to the response to El Niño and strongest in landmasses adjacent to the Pacific. The authors found that indices of more rare precipitation events consistently show a weaker response to circulation than indices of moderate extremes.

Changing northern hemisphere snow seasons. Choi G, et al. (2010). *Journal of Climate,* 23:5303-5310. http://dx.doi.org/10.1175/2010JCLI3644.1

Snow cover contributes to the suppression of surface air temperature and serves as a reservoir for supplying water for ecosystems, irrigation and human consumption. Early spring snowmelt is receiving increasing attention as an indicator of climate variability and change.

This paper examines spatial and temporal patterns in the onset, offset and length of the snow season over four decades across Northern Hemisphere continents. Weekly snow cover extent data from 1967 to 2008 were used to define the initiation and termination of snow seasons across the Northern Hemisphere. Data were obtained from NOAA and National Ice Center meteorologists, primarily using visible satellite imagery. The authors define two snow seasons: (1) full snow season (FSS) is the interval between the first appearance (onset) and last disappearance (offset) of snow cover and (2) continuous snow season (CSS) is the longest interval of the season with an unbroken string of weeks for which a location (grid cell) is snow-covered.

FSS duration decreased at a rate of 0.8 week per decade (5.3 days per decade) during the 1972/73–2007/08 time period. The observed reduction in FSS duration is attributed to earlier FSS offset dates throughout North America and Eurasia. FSS offset advanced at a rate of −0.8 week per decade (−5.5 days per decade) since the early

1970s. Earlier offsets of one to several weeks are most notable in the mountainous western United States, Western Europe, and central and East Asia. No appreciable changes in the FSS onset or in any CSS variable are found, although there are regional variations that are a week or longer.

The authors concluded that differences in changes between FSS and CSS may be associated with the relationship between temperature and snowmelt: during late winter and early spring, the temperature may be just warm enough to lead to melt, while in the winter, even when temperatures are above average, they may still be below freezing. Furthermore, with increasing spring solar radiation, enhanced snow–albedo feedback may reinforce snow melting processes.

Trends in rainfall exceedances in the observed record in selected areas of the United States. Bonnin GM, et al. (2011). *Journal of the American Water Resources Association*, 4 (6):1173-1182. http://dx.doi.org/10.1111/j.1752-1688.2011.00603.x

This paper highlights the differences in how the potential impacts of climate change on precipitation are quantified by climate scientists and by civil engineers. The authors note that metrics reported in the climate change literature do not address the much higher rainfall depths and intensities that cause flooding or that are of concern to civil engineers for the design of infrastructure such as stormwater drains and floodplain management. Civil engineers and planners rely on precipitation frequency estimates defined in terms of average annual exceedances probabilities or average recurrence intervals. The authors examine trends in the observed record in the frequency of rainfall exceedances in two selected regions: the Semiarid Southwest (which includes inland portions of southeast California and the Ohio River Basin.

The estimated trends in exceedances at one-day and multiday durations were statistically significant and increasing for the Ohio River Basin and surrounding states but the reverse was true for the Semiarid Southwest (i.e., not significant and decreasing trends). The magnitude of the trends was small for all but the more frequent events and also small with respect to the uncertainty associated with the precipitation frequency estimates themselves.

Storms, floods, and the science of atmospheric rivers. Ralph FM and Dettinger MD (2011). *Eos, Transactions American Geophysical Union*, 92(32):265. http://dx.doi.org/10.1029/2011EO320001

This article on atmospheric rivers (AR) describes their significance, the current state of knowledge, and studies underway to better understand them. Atmospheric rivers are narrow corridors of water vapor transport in the lower atmosphere that traverse long swaths of the Earth's surface as they bind together the atmospheric water cycle.

Research during the past decade has documented the importance of atmospheric rivers to the overall workings of the mid-latitude global water cycle. Historically, AR storms have been the sources of many floods in the Pacific coast states. At the same time, about one-third to one-half of California's precipitation is contributed by the ARs that make landfall in the state annually; a single typical AR storm can yield 2.5 to 5 cubic kilometers of precipitation, roughly 10 percent of the annual average runoff of the entire Sacramento River basin

Research to understand and predicting ARs, while relatively recent elsewhere, has been vigorous on the West Coast for over a decade. The dual roles of atmospheric rivers as hazards and water resources in many coastal regions may become a more pressing issue under anthropogenic climate change, which may alter both hazardous and productive aspects of these storms.

Human contribution to more-intense precipitation extremes. Min S-K, et al. (2011). *Nature*, 470:378-381. http://dx.doi.org/10.1038/nature09763

Understanding past changes in the intensity of heavy precipitation events and climate extremes is critical for reliable projections of future changes. Due to global warming, atmospheric water content has been increasing roughly exponentially with temperature. Human induced increases in greenhouse gases have contributed to the observed intensification. In this paper, observed and simulated changes in the annual maxima of daily and five-day consecutive precipitation amounts were compared for 1951-1999. These indices characterize extreme events that often cause impacts on society. In addition, since these annual extremes can be used to estimate the probability of rare events such as 100-year return values, they are used in the design of infrastructure. Model simulations were prepared using the Hadley Centre global land-based gridded climate extremes data set (HadEX) and the Coupled Model Intercomparison Project Phase 3 archive. Observations were limited to Northern Hemisphere land areas due to insufficient data sets elsewhere.

Annual observations show overall increasing maximum rainfall trends over most of the covered areas for both daily and five-day precipitation amounts. The multi-model mean for anthropogenic forcing simulations showed similar positive trends, but with smaller amplitude than observed. The multi-model mean for simulations including all forcing exhibited similar moderate trends for daily precipitation, but a mixed pattern of moistening and drying for five-day precipitation. Five-year mean observations also exhibit increasing trends, and simulations with anthropogenic and all forcing show weaker and mixed trends as the annual comparisons did. Analysis indicates models underestimate extreme precipitation response to anthropogenic forcing compared to observed changes. Extreme precipitation events may amplify more quickly in the future than models have projected, and cause more severe effects than previously estimated.

Searching for information in 133 years of California snowfall observations.
Christy JR (2012). *Journal of Hydrometeorology*, 13(3):895-912.
http://dx.doi.org/10.1175/JHM-D-11-040.1

Long-term variations of snowfall have significant implications for natural and human engineered systems in California. In this study, monthly snowfall totals from over 500 stations in California, some of which date back to 1878, were examined. Most data were accessed through the NOAA archive, but several thousand station-months of data were separately keyed in from image files of original documents. Over 26,000 of these entries were new relative to the NOAA archive, generally providing data prior to 1920. The stations were then subdivided into 18 regions for the construction of representative time series of each area.

What appeared to be an opportunity to perform a straightforward assessment of snowfall variations over the past 13 decades ran into difficulties. There was inconsistent record-keeping and an increasing presence of snowfall values recorded as "zero" that instead should have been recorded as ''missing.'' This and other issues reduce the confidence that the regional time series are representative of true variations and trends, especially for regions with few systematically reporting stations. Interpreting linear trends on time series with infrequent large anomalies of one sign (i.e., heavy snowfall years) and unresolved data issues should be carried out with caution.

For those regions characterized by consistent monitoring and with the most robust statistical reproducibility, no statistically significant trends in their periods of record (up to 133 years) nor in the most recent 50 years were found. This result encompasses the main snowfall region of the western slope of the Sierra Nevada Mountains.

Addendum.

> **Comments on "Searching for information in 133 years of California snowfall observations".** Coats R (2013). *Journal of Hydrometeorology*, 14: 382.
> http://dx.doi.org/10.1175/JHM-D-12-070.1
>
> This commentary is a response to the study by Christy. Coats commented that Christy did a good job of describing and addressing some of the problems with using seasonal total snowfall as a time-trend metric. However, Coats contends that Christy overlooked the issue that variance in total annual (seasonal) snowfall at a station is largely driven by the variance in total annual (seasonal) precipitation. This makes it very unlikely that a trend in precipitation form will be detected using Christy's metric of total snowfall depth, especially in California. Christy should have removed the total precipitation effect by linear regression and tested for trends in the residuals, or at least divided seasonal snowfall depth by seasonal total precipitation. Alternatively, Christy could have examined trends in percent of precipitation falling with temperature below freezing. At Tahoe City, California, the latter approach shows a highly significant downward trend. Coats

also mentions that Christy should have stated what ‘‘simple statistical significance test’’ he used to test for time trends.

Reply to comments on “Searching for information in 133 Years of California snowfall observations”. Christy JR (2013). *Journal of Hydrometeorology*, 14: 383-386. http://dx.doi.org/10.1175/JHM-D-12-089.1

Coats raises issues regarding the utility of the snowfall metric presented by Christy in 'Searching for information in 133 years of California snowfall observations,' suggesting that variance issues need more attention and that alternative metrics would be more useful than snowfall. The variance question is further addressed in this reply to Coats’s commentary. Regarding other metrics, it is shown that they are either inconsistently measured for long-term analysis or are actually consistent with Christy's findings. In addition, Christy disagrees that Tahoe City, discussed by Coats, can be used to examine long-term precipitation trends because of inconsistent measuring practices through time. Christy concludes that his results remain unchanged.

Trends in United States Surface Humidity, 1930-2010. Brown PJ and DeGaetano AT (2013). Journal of Applied Meteorological Climatology, **52**: 147–163. http://dx.doi.org/10.1175/JAMC-D-12-035.1

Water vapor is a greenhouse gas that is intrinsically linked to climate change. Warming temperatures affect the amount of moisture in the air. Increasing evidence from observations and climate models indicate that human activity is increasing atmospheric moisture. Relative humidity (degree of saturation of the air) and specific humidity (amount of water vapor in the air) are the primary measures of atmospheric moisture. This study investigates data on the humidity in the United States since the 1930s and examines trends in temperature and atmospheric moisture variables. 145 stations were used to identify annual and seasonal changes in temperature, dew point (the temperature at which the air must be cooled to reach saturation), relative humidity, and specific humidity since 1930.

Because of many systematic instrument changes that have occurred, a homogeneity assessment was performed on temperatures and dew points. There is evidence of inhomogeneity in the relative humidity record that mostly affects data from before 1950, indicating that long-term decreases in relative humidity should be viewed with caution. Dew points contained higher breakpoint detection rates associated with instrument changes than did temperatures. Temperature trends were lessened by adjusting the data, whereas dew points were unaffected. Effects stayed the same whether the adjustments were based on statistically detected or fixed-year breakpoints.

Average long-term trends over the time period 1930-2010 show that the temperature has warmed, especially since 1980, but there has been little change in dew point and specific humidity. Warming is strongest in the spring. Trends since 1947 suggest that

the warming of temperatures has coincided with increases in dew points and moistening of specific humidity. This moistening is pronounced in the summer in the Midwest.

For the United States overall, trends in relative humidity show little change between 1947 and 2010, a time period with data that is more homogenous. Moistening has occurred throughout the central U.S. while other regions have experienced drying. The effects of urban-related warming and drying are minimal. The authors concluded that the regional changes in atmospheric moisture appear to be related to regional changes in land use and moisture availability.

Historical and national perspectives on extreme west coast precipitation associated with atmospheric rivers during December 2010. Ralph FM and Dettinger MD (2012). *Bulletin of the American Meteorological Society*, 93:783-790. http://dx.doi.org/10.1175/BAMS-D-11-00188.1

Strong winter storms battered the United States west coast from Washington to southern California in December 2010, producing as much as 250-670 millimeters (mm) (10-26 inches) of rain in mountainous areas. A common denominator among these events is a series of strong atmospheric rivers (ARs) that transported large amounts of water vapor from over the Pacific Ocean to the West coast.

The authors pose the questions: How *extreme* were these events relative to other AR cases in the region, and, how does west coast AR-fed precipitation compare with extreme precipitation in other parts of the U.S., such as from hurricanes and tropical storms? This study uses decades of Cooperative Observer (COOP) daily precipitation reports during 1950-2008 from 5,877 stations across the U.S. to address these questions and provides an analysis of the December 2010 West Coast events and their associated weather forecasts.

The method developed to rank rainfall events is based on a simple scaling that uses 72-hour total precipitation accumulations. The scale has four Rainfall Categories (i.e., R- Cat 1 = 200-299 mm; R-Cat 2 = 300-399 mm; R-Cat 3 = 400-499 mm; and R-Cat 4 >500 mm). On average there have been 48, 9, 2 and 1 events per year, respectively, that reach these thresholds in the conterminous U.S. This analysis found that extreme precipitation events in the mountains of California are comparable with the strongest events elsewhere nationally, which occur in the Southeastern U.S. (including Texas). The California storms are predominantly due to land falling ARs, while the events in the Southeastern U.S. include the effects of land falling tropical storms and hurricanes. In addition to allowing a comparison of AR-related extreme precipitation on the U.S. West coast with extreme precipitation events elsewhere, the authors suggest this scaling could be helpful in communicating precipitation risks and event magnitudes to the public and for monitoring for trends in extreme precipitation event frequency within a changing climate.

Droughts

Droughts are extreme climate events characterized by period of abnormally dry weather long enough to cause a serious hydrological imbalance. Droughts can have significant impacts on the environment, agriculture, public health, the economy, and societies as a whole. Shortage of precipitation during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought). During the runoff and percolation season, precipitation deficits affect water supplies. In addition to reductions in precipitation, changes in soil moisture and groundwater are also affected by increases in evaporation and evapotranspiration.

Water, climate change and sustainability in the southwest. MacDonald G (2010). *Proceedings of the National Academy of Sciences*, 107:21256-21262. http://dx.doi.org/10.1073/pnas.0909651107

The purpose of this paper is to assess current and future drought and chronic water-related challenges in the United States Southwest and consider the problems and prescriptions for 21st-century sustainability. A particular focus is placed on the potential impact of greenhouse warming on current and future hydroclimatology. Issues include temperature increases, decreasing precipitation, recent droughts, decreasing irrigated farmland, population growth and domestic water demand, with specific references to California.

The author reviews research papers on various aspects of water sustainability using an array of approaches that include analysis of current meteorological, socioeconomic, and ecological data, paleoenvironmental data analysis, model simulations, and policy analysis. Several important insights emerge—some of which are particularly noteworthy because they arise from more than one research approach. These insights are organized around four critical questions:

- Is the early 21st-century drought exceptional compared with earlier droughts and is this attributable to increasing greenhouse gases?
- Is it likely that the Southwest will experience a more arid climate due to global climate change driven by increasing greenhouse gases?
- What are the potential impacts of increasing aridity on wildland and urban/suburban systems?
- What policy prescriptions and other strategies might help us to develop water-use sustainability in the Southwest?

The author ends by stating that because climate warming will exacerbate water sustainability problems, the Southwest is likely to experience some of the highest economic expenses and environmental losses related to climate change.

Drought under global warming: A Review. Dai A (2011). *Wiley Interdisciplinary Reviews: Climate Change*, 2(1):45-65. http://dx.doi.org/10.1002/wcc.81

This review article discusses recent literature on drought of the last millennium, followed by an update on global aridity changes from 1950 to 2008. Projected future aridity is presented based on recent studies and the authors' analysis of model simulations. Highlighted below are key points discussed in further detail in the article:

- Regions like the United States have avoided prolonged droughts during the last 50 years due to natural climate variations, but might see persistent droughts in the next 20–50 years under climate change.
- Dry periods lasting for years to decades have occurred many times during the last millennium over regions like North America, West Africa, and East Asia. These droughts were likely triggered by anomalous tropical SSTs, with La Nina-like SST anomalies leading to drought in North America, and El-Nino-like SSTs causing drought in East China.
- In the 1970s and 1980s, West Africa experienced a series of severe and widespread droughts called Sahel droughts. The Sahel droughts in the 1970s and 1980s have been linked to a southward shift of the warmest SSTs in the Atlantic and warming in the Indian Ocean.
- Local feedbacks, such as increased evaporation and humidity associated with dry soils and high temperatures, may enhance and prolong drought.
- Global aridity has increased substantially since the 1970s due to recent drying over Africa, southern Europe, East and South Asia, and eastern Australia. Although natural variations in ENSO, tropical Atlantic SSTs, and Asian monsoons have played a large role in the recent drying, the rapid warming since the late 1970s has increased atmospheric demand for moisture and likely altered atmospheric circulation patterns. A large part of the warming is attributed to greenhouse gas emissions.
- Climate models project increased aridity in the 21st century over most of Africa, southern Europe and the Middle East, most of the Americas, Australia, and Southeast Asia.
- Future efforts to predict drought will depend on models' ability to predict tropical SSTs.

Given the dire predictions for drought, the review emphasizes that adaptation measures for future climate changes should consider the possibility of increased aridity and widespread drought in coming decades. It concludes that lessons learned from dealing with past severe droughts, such as the Sahel drought during the 1970s and 1980s, may be helpful in designing adaptation strategies for future droughts.

Increasing drought under global warming in observations and models. Dai A (2013). *Nature Climate Change*, 3:52-58. http://dx.doi.org/10.1038/nclimate1633

Historical records of precipitation, streamflow and drought indices all show increased aridity since 1950 over many land areas. Analyses of model-simulated soil moisture, drought indices and precipitation-minus-evaporation suggest increased risk of drought in the twenty-first century. There are, however, large differences in the observed and model-simulated drying patterns. Reconciling these differences is necessary before the model predictions can be trusted. Previous studies show that changes in SST have large influences on land precipitation and the inability of the models to reproduce observed regional precipitation changes is linked to the lack of the observed, largely natural change patterns in SSTs in model simulations.

To study how drought might change under increasing GHGs, the author analyzed climate model simulations under possible future GHG emissions scenarios. The author shows that the models reproduce not only the influence of El Niño-Southern Oscillation on drought over land, but also the observed global mean aridity trend from 1923 to 2010. Regional differences in observed and model-simulated aridity changes result mainly from natural variations in tropical SSTs that are often not captured by the models. The unforced natural variations vary among model runs owing to different initial conditions and thus are irreproducible.

The author concludes that the observed global aridity changes up to 2010 are consistent with model predictions, which suggest severe and widespread droughts in the next 30–90 years over many land areas. The author noted that droughts result from either decreased precipitation and/or increased evaporation.

Extreme events

An extreme climate event is one that has appeared only rarely in the historical record, such as a 1-in-100 year flood or a three-day heat wave that is hotter than 95 percent of all previous 3-day heat waves. 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). Further, there is evidence of human influence on some extremes. However, determining whether a specific single extreme event is due to human influence is difficult. Extreme events usually result from a combination of factors, some strongly affected by human activities, some not. Nevertheless, climate models can be used to determine whether human influences have changed the likelihood of certain types of extreme events.

Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities? Stone B, et al. (2010). *Environmental Health Perspectives*, 118(10):1425-1428. http://dx.doi.org/10.1289/ehp.0901879

Extreme heat events (EHEs) are increasing in frequency in large United States (U.S) cities and are responsible for a greater annual number of climate-related fatalities, on average, than any other form of extreme weather. Urban form—that is, the characteristics and patterns of urban development, including "centeredness" (the proximity of the metropolitan population to a central business district and related measures of population density), "connectivity" (the density of the street network or the number of intersections per unit area), population density distributions, and land use mix—can intensify EHEs in cities. This is due to the loss of vegetation with accompanying loss of evapotranspiration; increased dark surfaces which absorb and then reradiate heat; building configurations that trap heat; and the concentrated generation of heat from vehicles and other sources. Cities have significantly decentralized over recent decades in a pattern known as urban sprawl. Sprawl features geographic expansion over large areas, low-density land use, low connectivity, and heavy reliance on automobiles.

The authors tested the hypothesis that sprawling patterns of metropolitan land use are more closely associated with the rate of increase in EHEs than are compact patterns of metropolitan land use. They examined the correlation between the rate of increase of EHEs over a five-decade period (1956-2005) and a widely published "sprawl index" as a measure of urban form. Previously published sprawl index values developed for the largest U.S. metropolitan regions (53 of the 83 values) based on data from the 2000 Census and other national surveys were used. The extreme heat event data were drawn from a heat stress index maintained for 187 U.S. cities by the National Climatic Data Center. The authors measured the correlation between the mean annual change in the number of EHEs between 1956 and 2005 and the sprawl ranking of each region in 2000.

An analysis of trends in excessively hot days over the five decades found the frequency of EHEs to be increasing significantly on an annual basis. The rate of increase in the annual number of EHEs in the most sprawling metropolitan regions was more than double the rate of increase observed in the most compact metropolitan regions. These findings were independent of climate zone, metropolitan population size, or the rate of metropolitan population growth. According to the authors, this study highlights the importance of urban design strategies in reducing vulnerability and adapting to the heat-related health effects associated with ongoing climate change.

Increasing prevalence of extreme summer temperatures in the United States. Duffy PB and Tebaldi C (2012). *Climatic Change*, 111:487-495. http://dx.doi.org/10.1007%2Fs10584-012-0396-6

Extreme June, July, and August temperatures are occurring more frequently in parts of the contiguous United States. The researchers first compared the period 1975-2000 to the preceding 25 years, and found by using observations and 16 global climate models, that in certain regions, summertime average temperatures that were rare (that is, at or above the 95th percentile) in the earlier period occurred more often in the later period; the increases in rare summer temperatures in the later period are very unlikely to have occurred through chance weather variations (such as El Niños or La Niñas). The agreement between observations and models demonstrates that the models are able to simulate changes in the occurrence of extreme summertime temperatures. Using results obtained from climate models for 1995-2024, the researchers found that summer temperatures that were extreme during 1950-1979 occur more often in the later time period—a finding that supports the conclusion that the increase is very unlikely to be due to chance weather variations alone, such as El Niños or La Niñas.

Finally, results were modeled for 2035-2064 (representing the middle of this century). Extreme summertime temperatures that were rare during 1950-1979 are projected to occur in most summers throughout the 48-state region in the mid-century period. Mid-century summertime mean temperatures that historically occurred only five percent of the time are projected to occur at least 70 percent of the time everywhere in the 48-state region. The noted increase in extremes in the Southwest and Northeast are explained by strong historical and projected warming there. This result is based upon assuming a commonly used scenario for future emissions of CO_2, the main driver of human-caused climate change.

Climate change: A new metric to measure changes in the frequency of extreme temperatures using record data. Munasinghe L, et al. (2012) *Climatic Change,* 113:1001-1024. http://dx.doi.org/10.1007/s10584-011-0370-8

Among the lines of evidence for global warming is the increased frequency of extreme climate events including record high temperatures. This paper presents a global assessment of climate change by analyzing changes in extreme high and extreme low temperatures over the past century. The authors present a metric they developed called “record equivalent draws (RED).” This metric is based on a statistical method that uses record high and low temperature observations and approximates changes in the likelihood of these extreme high/low temperatures. REDs can aggregate temperatures from heterogeneous distributions, and can address whether warming or cooling is truly global, as well as allow for a comparison of changes in the frequency of extreme temperatures across vastly different climates and geographic regions.

Based on monthly average temperatures, the frequency of extreme high temperatures increased ten-fold between the first three decades of the last century (1900-1929) and the most recent decade (1999-2008). These estimates reproduced the general patterns of warming and cooling indicated by changes in mean temperatures over the past century; however, disaggregated analyses yielded estimates that provided new information on the spatial patterns of the warming, including new insights into climate

changes, regional and seasonal variability. For example, mean temperatures did not increase in the tropics as much as it did in higher latitudes, the increase in frequency of extreme high temperatures is greater in the tropics. The RED estimates also suggest concurrent increases in the frequency of extreme high and extreme low temperatures during a period when global mean temperature plateaued (2002-2008). The authors note that the RED metric can be applied more widely to study other climate components such as sea surface temperature and precipitation.

California heat waves in the present and future. Gershunov A and Guirguis K (2012). *Geophysical Research Letters.* 39(18), L18710.
http://onlinelibrary.wiley.com/doi/10.1029/2012GL052979/abstract

California heat waves are becoming more humid and expressed with disproportionate intensity in nighttime rather than daytime temperatures which are typically dry heat. This trend is already clearly observed and modeled to various degrees over all sub-regions of California especially in the coastal regions. Given the high coastal population density and their low acclimatization to heat, especially humid heat, this trend bodes ill for these communities, jeopardizing public health and stressing energy resources. This paper examines current and projected heat waves throughout California and its sub-regions using observations and global climate model simulations.

The authors used observed daily maximum and minimum temperature station source data from the National Climatic Data Center. Daily sea level pressure and precipitable water data (humidity) were derived from NOAA's Climate Prediction Center. Four models were chosen for their ability to simulate seasonal features of California's climate and observed climate variability and were validated for their ability to realistically simulate heat waves. Heat waves were defined as daily temperature excesses over a threshold (Tmax and Tmin) reported between May and September spanning the years 1950-1999. The heat wave index (HWI) was used as a measure of the frequency, intensity and duration of heat waves, and local daytime HWI over the 50-year base period was analyzed to identify the primary patterns of summertime heat wave variability. Instead of defining heat waves relative to fixed temperature thresholds, the researchers projected heat wave intensity against a backdrop of increasing average summertime temperature. This "non-stationary" approach allows the definition of heat waves to evolve with the changing climate and reflect extreme conditions relevant to the climate of the time.

The non-stationary analysis suggested a trend toward more humid heat-waves expressed very strongly in elevated nighttime temperatures. It suggests that heat waves in hot desert regions will likely become less intense relative to strong inland warming, especially at night. Moreover, relative to local warming, the mid-summer heat-waves are projected to get stronger in cooler coastal areas. The authors note that this trend has strong public health implications in coastal communities that lack air conditioning and a physiological tolerance to heat.

Surface urban heat island across 419 global big cities. Peng S, et al. (2012). *Environmental Science and Technology*, 46(2):696-703. http://dx.doi.org/10.1021/es2030438

A better understanding of the drivers of urban heat island intensity is of critical importance for climate research and impacts studies, with strong implications for urban planning. In this study, the authors assessed the diurnal and seasonal variation of surface urban heat island intensity (SUHII) in cities across the globe. SUHII is defined as the surface temperature difference between urban area and suburban area as measured by satellite imaging. The primary objective is to quantify the between-city differences in surface urban heat island and to gain insights on its linkage to biophysical drivers such as vegetation greenness, albedo effect, and to socio-economic drivers such as population density.

The authors used the Land Surface Temperature (LST) data set from satellite remote sensing (MODIS-Aqua) during the period 2003−2008 to determine the intensity of the surface urban heat island over 419 big cities (with populations of more than 1 million). To explore the global drivers of surface urban heat islands, satellite observations of vegetation index, albedo, climate, and several socio-economic indices were combined. Data for each urban and suburban area included air temperature and precipitation for the years 1971−2000. Population density and remotely sensed nighttime light served as a proxy of socio-economic activities. Both seasonal and annual averaged daytime and nighttime SUHII were computed. The spatial differences of SUHII among big cities were studied for the period 2003−2008.

Across the cities, the authors show that the average annual daytime SUHII is higher than the annual nighttime SUHII. There was no correlation between daytime and nighttime SUHII across the cities, suggesting different driving mechanisms between day and night. The distribution of nighttime SUHII correlated positively with the difference in albedo and nighttime light between urban area and suburban area. The distribution of daytime SUHII correlated negatively across cities with the difference of vegetation cover in urban and suburban areas, suggesting the role of urban vegetation in lowering temperatures.

Results from this study emphasize the key role of vegetation feedback in attenuating daytime SUHII of big cities, further highlighting that increasing urban vegetation cover could be one effective way to mitigate the urban heat island effect.

Heat waves in the United States: Definitions, patterns and trends. Smith T, et al. (2013). *Climatic Change*, 118(3-4):811-825. http://dx.doi.org/10.1007/s10584-012-0659-2

There are diverse perspectives on what precisely constitutes a *heat wave* and climate scientists, public health researchers and communities may have different definitions.

While a heat wave is generally understood to be a period of extreme and unusual warmth, quantitative definitions differ in (1) the metric of heat used (e.g., daily mean temperature, daily maximum temperature, temperature and humidity); (2) the manner in which thresholds of exceedance are defined (absolute threshold or relative threshold); and (3) the role of duration in a heat wave definition (e.g., one day or multiple length criteria). The lack of a unified index can cause confusion when discussing climate trends and impacts of climate change.

This paper analyzes geographic patterns and trends for the Continental United States in 15 previously published heat wave indices (HIs). The objective was to understand how the choice of definition influences conclusions regarding the observed frequency of extreme heat events in different regions in order to provide a baseline for interpreting studies that project future trends in these events. Meteorological data for the months of May through September for the years 1979-2011 were obtained from the North American Land Data Assimilation System. HIs were divided into two groups – relative thresholds and absolute thresholds—and statistical analyses were performed to assess trends. To gain insight into regionalized patterns of HI, six regions were evaluated: Northwest, Southwest (including California), Great Plains, Midwest, Southeast and Northeast.

For both the relative and absolute HI, the Southeast saw the highest values of average heat wave days, indicating that this region has experienced more heat wave days during the period than any other region. From the trend analysis, the Southeast and Great Plains regions experienced both the largest magnitude and most widespread increases in heat wave days per year. Significant negative trends, although rare, were found in portions of the Southwest, Northwest and Great Plains. The researchers noted that similar comparisons can be performed for other meteorological datasets and for future climate projections in order to explore the full range of heat wave impacts associated with climate variability and change.

Historical and national perspectives on extreme west coast precipitation associated with atmospheric rivers during December 2010. Ralph FM and Dettinger MD (2012). *Bulletin of the American Meteorological Society*, 93:783-790. http://dx.doi.org/10.1175/BAMS-D-11-00188.1

See summary under *Changes in climate, Precipitation*, page 8888.

Human contribution to more-intense precipitation extremes. Min S-K, et al. (2011). *Nature*, 470:378-381. http://dx.doi.org/10.1038/nature09763

See summary under *Changes in climate, Precipitation,* page 85.

Explaining Extreme Events of 2012 from a Climate Perspective. Peterson TC, et al. (Eds.) (2013). *Bulletin of the American Meteorological Society*, 94(9):S1-S74. http://www.ametsoc.org/2012extremeeventsclimate.pdf

See summary under *Authoritative Reports*, page 33.

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 summarizes publications on: changes in ocean temperature and circulation; upwelling; ocean chemistry; sea level rise; glaciers; 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^{o}C. 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]

Ocean circulations, heat budgets, and future commitment to climate change.
Pierce DW, et al. (2011). *Annual Review of Environment and Resources*, 36:27-43.
http://dx.doi.org/10.1146/annurev-environ-022610-112928

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

Climate scientists predict that the Earth's surface will continue to warm for decades, and the sea level will rise for centuries, even if the atmospheric concentration of GHGs is held fixed at current levels. This is referred to as "committed" climate change because it is unavoidable. Committed climate change arises due to the large thermal inertia of the oceans and their consequent time lag in adjusting to altered GHG concentrations. This paper describes the basic heat balance of the oceans, the physical reasons for the long time lag in ocean temperature and sea-level rise and the observational evidence for human-induced ocean warming over the past 50 years.

Highlighted below are summary points discussed in the review:

- Subsurface measurements over the past 50 years show a significant increase in ocean heat content, which has no possibility of being contaminated by urban heat island effects.
- Surface ocean temperatures can adjust to higher greenhouse gas concentrations in a decade, but deep ocean water takes millennia to reach a new equilibrium.
- Observed ocean warming is outside the expected range of natural climate variability and matches, by basin and depth, the signal expected from human effects on the climate.
- Although the committed level of warming and sea-level rise is now unavoidable save for massive geoengineering efforts, the ultimate amount of climate change Earth experiences depends largely on what steps, if any, humans take soon to limit emissions of GHGs to the atmosphere.

Physics of U.S. surface temperature response to ENSO. Zhang T, et al. (2011). *Journal of Climate*, 24:4874-4887. http://dx.doi.org/10.1175/2011JCLI3944.1

The purpose of this paper is to elucidate physical processes affecting how surface temperatures in the U.S. respond to the ENSO. This study focuses on the impact of ENSO on the U.S. hydrologic cycle during winter (December to February) on the hydrologic cycle response to El Niño and La Niña sea surface temperature forcing over the continental U.S. Observational data from meteorological databases were used to study the surface energy balance, highlighting the role of clouds, water vapor, and properties associated with snow cover and soil moisture.

During El Niño, surface warming over the northern U.S. is physically consistent with three primary processes: 1) increased downward solar radiation due to reduced cloud *optical thickness* (transparency), 2) reduced reflected solar radiation due to snow cover loss, and 3) increased downward longwave radiation linked to an increase in precipitable water. During the winter season, U.S. surface temperature conditions associated with ENSO are determined principally by anomalies in the surface *radiative heating*—the sum of absorbed solar radiation and downward longwave radiation. Surface radiative heating is, in turn, linked with specific characteristics of the atmospheric hydrologic response to ENSO and also to feedbacks by the land surface response.

In contrast, surface cooling over the southern U.S. during El Niño is mainly the result of a reduction in incoming solar radiation resulting from increased cloud optical thickness. During La Niña, surface warming over the central U.S. results mainly from snow cover losses, whereas warming over the southern U.S. results mainly from a reduction in cloud optical thickness (that yields increased incoming solar radiation) and from an increase in precipitable water that enhances the downward longwave radiation.

The surface temperature anomalies during ENSO integrate the immediate effects of physical processes inherent in the energy balance with the ultimate causal effects linked to the free-atmospheric teleconnections. Two processes provide this linkage. First, there exists a strong connection between the convergence of the atmospheric water vapor transport (which largely results from the storm-track shifts during ENSO) and the cloud optical thickness. The latter affects the downward shortwave radiation, a key contributor to the surface energy balance. Second, the ENSO-generated teleconnection pattern and related tropospheric column temperature control the column precipitable water and the resulting changes in downward longwave radiation, a second major contributor to the surface energy balance.

The authors' findings present a relatively detailed picture for understanding the physics of the U.S. surface temperature response to sea surface temperature forcing. They suggest that these findings may be useful for the validation of climate models used in seasonal forecasting and for understanding the U.S. surface temperature response to anthropogenic greenhouse gas forcing in nature and in models used for climate-change projections.

The enhanced drying effect of Central-Pacific El Niño on US winter. Yu J-Y and Zou Y (2013). *Environmental Research Letters*, 8(1):014019. http://dx.doi.org/10.1088/1748-9326/8/1/014019

The climate in the U.S. is significantly influenced by El Niño events in the tropical Pacific. It has recently been recognized that there are two different types of El Niño: the Eastern Pacific (EP) El Niño and the Central Pacific (CP) El Niño. EP El Niño events are characterized by SST anomalies extending along the equator westward from the South American Coast, while the CP El Niño events are characterized by SST anomalies mostly confined to a region near the equator around the international dateline. While the EP type used to be the conventional type of El Niño, location of El Niño has shifted more to the CP in recent decades.

The authors investigated the recently emerged CP type of El Niño using statistical analyses, numerical model experiments and case studies. SST data from NOAA, and precipitation and wind data were used to identify monthly SST, precipitation, and wind anomalies from 1948-2010. Monthly values of an EP El Niño Index and CP El Niño Index were used to represent the intensities of the two types of El Niño. An

atmospheric general circulation model was used to assess the impacts of the two types of El Niño.

Analyses from this study indicate that the CP El Niño enhances the drying impacts produced by traditional EP El Niño events on U.S. winter precipitation. At the same time, CP El Niño weakens the wetting impacts produced by the EP El Niño events on the winter precipitation. As a result, the emerging CP El Niño produces an overall drying effect on the U.S. winter, particularly over the Pacific Northwest, Ohio–Mississippi Valley, and Southeast. The southern end of the Southwest is the only region of the U.S. that is exempted from the drying effect produced by El Niño when it shifts from the EP type to the CP type.

The authors suggest that the results have the following implications: (1) Droughts in the Ohio-Mississippi Valley and Pacific Northwest during El Niño may be intensified after the El Niño becomes more of the CP types, while the Southwest should prepare for more flooding events during the CP El Niño years; and (2) The shift of the El Niño from the EP type to CP type in recent decades may have produced a net drying effect on U.S. winter precipitations, except for the Southwest.

Recent global-warming hiatus tied to equatorial Pacific surface cooling. Kosaka Y and Xie S-P (2013). *Nature*, 501:403-407. http://dx.doi.org/10.1038/nature12534

See summary under *Changes in Climate, Temperature*, page 81.

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 upward, 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.

Observations of increased wind-driven coastal upwelling off central California. Garcia-Reyes M and Largier J (2010). *Journal of Geophysical Research: Oceans*, 115(C4):C04011. http://onlinelibrary.wiley.com/doi/10.1029/2009JC005576/abstract

Upwelling regions off the coast of central California have significant ecological and economic importance. Observed and projected increases in global temperature raise the question about how the upwelling process and, in consequence, the coastal ocean ecosystem, will change. As early as 1990, scientists proposed that global warming should lead to intensification of the continental thermal lows adjacent to upwelling regions. This intensification would be reflected in increased onshore-offshore atmospheric pressure gradients, enhanced alongshore winds, and accelerated coastal

upwelling circulation that would result in cooling of the ocean surface. This paper studied the variability of alongshore wind-driven coastal upwelling off central California (35°N-39°N) from 1982 to 2008, focusing on direct observations of upwelling winds and sea temperatures.

Hourly wind and SST data from buoys over the California shelf were used to study coastal upwelling conditions at different latitudes. Upwelling conditions are present at most locations in most years from March to July, therefore this period was used as a standard upwelling season to compare trends in upwelling intensity across sites. Upwelling was characterized using the number of days with upwelling conditions, and a coastal upwelling index from NOAA (a measure of upwelling strength). In addition, time series data of climate indices like the PDO and the North Pacific Gyre Oscillation (NPGO) from NOAA and the Georgia Institute of Technology were analyzed.

A long-term increase in coastal upwelling was observed in central California during the 26-year period, specifically from Monterey Bay to Bodega Bay. There were stronger upwelling-favorable winds, colder waters, and more frequent upwelling days during the upwelling season (March-July). A longer upwelling season was observed in the same region, starting earlier in the spring and lasting later in the fall. Changes in alongshore wind (forcing of upwelling) were poorly correlated with the ENSO or the PDO. The Northern Oscillation (NO) and the NPGO (NPGO), on the other hand, correlated with upwelling-favorable winds in the region. Changes in SST correlated with changes in wind and the climate indices. Although the record is too short to statistically separate the observed trends from the influence of decadal oscillations associated with NO, NPGO, ENSO and PDO, the localized region where the trends are observed and their correlation with similar trends in the NO and NPGO indices suggest a change in the strength of wind-driven coastal upwelling rather than a change in the conditions of the California Current. The authors note that observed changes and model predictions suggest that a long time trend in global temperatures may have already led to increased upwelling off central California and perhaps also in other coastal upwelling regions.

Seasonality of coastal upwelling off central and northern California: New insights including temporal and spatial variability. García-Reyes M and LargierJL (2012). *Journal of Geophysical Research: Oceans*, 117:C03028. http://dx.doi.org/10.1029/2011JC007629

The coastal ocean environment off California is largely determined by coastal upwelling, and its ecosystem is tightly coupled to seasonality in this upwelling. Although this seasonality has been long recognized, many descriptions are based on short-term or coarse-scale data, focus only on the upwelling season, or fail to capture aspects most relevant to the ecosystem—such as the transition time from winter to upwelling conditions (which, if delayed, could cause failures in biological productivity), or the differences in upwelling during the year (which determines when different species of phytoplankton bloom). In California, long time series of measured data are available now from satellites, radar and buoys. These help to describe the seasonality of coastal

upwelling and coastal conditions robustly, increasing our understanding of local-scale interactions of processes within the coupled ocean/land/atmosphere system. They provide more accurate quantification of the deviations from the seasonal cycle and a better understanding of the nature of such anomalies and their effects on the coastal conditions and the ecosystem.

This study analyzes 29 years of measured data from the Californian coast to describe the seasonality of winds that force upwelling and the response in coastal ocean temperatures. Time series of hourly wind velocity and SST from 1982 to 2010 were obtained from 9 coastal buoys maintained by the National Data Buoy Center of NOAA. Local winds were compared with upwelling (using the "upwelling index," derived from measurements of large-scale atmospheric pressure gradients across the coast) to identify key differences through the year and to explore the role of local features in modifying coastal winds. Seasonal anomalies in winds and temperatures at intra-annual and inter-annual timescales were compared to large-scale climate oscillations to investigate the influence of large-scale dynamics on coastal conditions. Satellite-based measurements (one decade of data) of chlorophyll concentration were used to examine the effect of coastal upwelling on primary productivity.

Distinct spatial and seasonal temporal patterns were evident. Based on alongshore wind stress characteristics, three seasons are defined: *Upwelling Season* (April-June) with strong, highly variable upwelling-favorable winds; *Relaxation Season* (July-September) with weak equatorward winds and low variability; and *Storm Season* (December-February) characterized by weak mean wind stress but large variability. The seasonality of upwelling reflects the interplay of three factors: coastal winds, large-scale winds, and offshore and remote ocean conditions. Ocean conditions, in particular surface temperature, affect large-scale and local winds. The strength of upwelling and the depth from which waters are upwelled are determined not only by local wind-forcing but also by the strength and depth of the thermocline, which is related to the large-scale thermocline in the California Current and the North Pacific. In parallel, seasonal alongshore flow and primary productivity are also controlled by local winds, large-scale winds and ocean conditions. Thus by clarifying the seasonal structure in upwelling (winds and temperature) and the primary factors influencing this seasonality there is an improved understanding of seasonal variability in marine population processes.

Integrated assessment of wind effects on Central California's pelagic ecosystem.
Garcıa-Reyes M, et al. (2013). *Ecosystems,* 16(5):722–735.
http://dx.doi.org/10.1007/s10021-013-9643-6

Along the California Current, there is strong evidence that winter upwelling preconditions the coastal ecosystem for the primary growing season. It is also possible that winter and early spring upwelling allows key species (plankton and forage fish) the time needed to develop further before the period of productivity begins. This study builds upon earlier work that tests the hypothesis that winds and the oceanic conditions and response to upwelling have distinct seasonal modes of variability and that these

modes differentially relate to pelagic marine life in the central California Current ecosystem.

Local upwelling from 1988-2010 along the United States west coast was calculated using both winter and spring/summer modes of upwelling, measured by local wind measurements and SST. The upwelling data were compared to 15 fish and seabird response variables (e.g., egg laying, reproductive success). Thus, multivariate indicators of upwelling and upper-trophic ‘‘productivity’’ were used to summarize the climate–biology relationships identified.

SST was a better predictor of most biological responses and both SST and wind were better predictors than the traditional upwelling index. In the local ecosystem, the most influential period of upwelling was found to be from January to May, even though upwelling is strongest during summer. The authors noted that multivariate indicators are particularly appropriate for integrated ecosystem assessments of climatic influences on marine life because they reflect both structure and processes (upwelling and biological growth/productivity/timing) known to determine functions in marine ecosystems.

Ocean chemistry

Ocean chemistry is influenced by many physical and biological processes, including currents, sediments, atmospheric constituents and ecological systems. Changes in ocean chemistry can have profound impacts on marine ecosystems, coastal resources and even the water cycle. Increasing water temperatures have been linked to declines in dissolved oxygen, which has implications for ocean productivity, nutrient and carbon cycling and ecosystem stability. (Ocean acidification is discussed above in Drivers of climate change.)

Ocean deoxygenation in a warming world. Keeling R, et al. (2010). *Annual Review Marine Science*, 2:199–229. http://dx.doi.org/10.1146/annurev.marine.010908.163855

A potentially serious consequence of global warming is a decrease in the dissolved oxygen (O_2) content (deoxygenation) of the world’s oceans. O_2 is less soluble in warmer water, and global warming may increase upper ocean stratification, thereby reducing the O_2 supply to the ocean interior. Decreased O_2 has implications for ocean productivity, nutrient cycling, carbon cycling and marine habitat. The science of ocean deoxygenation is in its early stages (the impact of future global warming on ocean O_2 distributions was not recognized until the late 1990s), consisting mostly of clarifying information about what is possible or conceivable within large uncertainties. This review article describes what is known and not known about the controls on O_2 distribution in today’s oceans, dissolved O_2 changes over the past few decades and possible future changes, and impacts on estimates of ocean carbon uptake.

Based on evidence that O_2 changes already seem to be occurring—most notably in the North Pacific and tropical O_2 minimum zones (low oxygen zones)—significant changes can be expected. Significant O_2 declines have been reported at several locations along the western shelf of North America over the past 50 years. O_2 has declined in the source waters feeding the coastal upwelling, including the southward flowing California Current and the deeper, northward flowing California Undercurrent. These changes may have a connection with O_2 declines observed as far away as the subarctic and equatorial Pacific. Local factors are probably also involved. For example, increased longshore wind strength tied to global warming may be increasing upwelling and O_2 demand in California coastal waters. In the waters off Southern California, surface warming may have increased stratification, reducing ventilation of subsurface waters on the shelf.

O_2 declines are consistent with the predicted response to global warming in global ocean models. The relative rapidity of O_2 decreases in the subarctic Pacific and in coastal upwelling regions off the west coast of North America raises the threat of imminent impacts on marine habitat and fisheries. The authors note that advances in the understanding of how and why O_2 is changing will improve our ability to document the uptake of CO_2 by the ocean, with links to concerns about ocean acidification and nutrient cycling.

The fingerprint of human-induced changes in the ocean's salinity and temperature fields. Pierce DW, et al. (2012). *Geophysical Research Letters*, 39(21):L21704. http://dx.doi.org/10.1029/2012GL053389

Changes in the Earth's water cycle can alter the ocean's salinity field, which in the tropics and mid-latitudes is determined primarily by evaporation, precipitation, river discharge, and wind. Since the ocean represents over 70 percent of the Earth's surface and evaporation and precipitation data for surface freshwater flux across much of the globe is limited, the ocean's salinity field is an ideal place to look for the effects of changes in the water cycle. This paper examines whether human-induced climate change has affected world ocean salinity.

Since the ocean's salinity field is dynamically intertwined with the temperature field, the authors simultaneously considered both variables in the analysis. The detection and attribution analysis compared three-dimensional temperature and salinity fields using 20 global climate models to 50 years of observations from the National Oceanographic Data Center. Observed upper level (0–700 m) changes in the ocean's salinity and temperature fields from 60°S to 60°N were analyzed from the time period 1955–2004. The observations were compared to over 11,000 years of model simulations for the two fields.

The results show there has been a detectible change in the ocean's global salinity field, and the observed changes are inconsistent with natural causes, either internal to the climate system (such as the El Niño/Southern Oscillation and the Pacific Decadal Oscillation) or external (the sun, volcanoes). Changes are consistent with those

expected from human effects on the climate, which arise primarily from anthropogenically-induced changes in greenhouse gases and aerosols. Similar results were found for the temperature field. When salinity and temperature changes were analyzed together, an even stronger signature of human forcing on the ocean emerged. Results from this study add to the evidence that human forcing of the climate is already taking place and changing the climate in ways that will have a profound global impact in coming decades.

Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. Durack PJ, et al. (2012). *Science*, 336(6080):455-458. http://dx.doi.org/10.1126/science.1212222

The Earth's surface has warmed by 0.5ºC over the past 50 years. Warming of the Earth's surface and lower atmosphere can strengthen the water cycle, largely due to the ability of warmer air to hold and redistribute more moisture. Wet regions are expected to become wetter, and dry regions are expected to become drier. The water cycle intensification is an enhancement in the patterns of exchange between evaporation and rainfall. With oceans accounting for 71 percent of the global surface area, the changes in the water cycle will affect ocean surface salinity.

Previous studies have struggled to determine coherent estimates of water cycle changes from land based data because surface observations of rainfall and evaporation are sparse. In this study, the authors address water cycle changes by instead analyzing ocean data. By looking at observed ocean salinity changes and the relationship between salinity, rainfall and evaporation in climate models, the authors determined the water cycle has strengthened by four percent from 1950 to 2000. This is twice the response projected by current generation global climate models. The study shows that ocean salinity patterns express an identifiable fingerprint of an intensifying water cycle.

The authors also combined 50-year (1950-2000) observed global surface salinity changes with changes from global climate models and found robust evidence of an intensified global water cycle at a rate of about 8 percent per degree of surface warming. The patterns are not uniform, with regional variations agreeing with the mechanism in which wet regions get more wet and dry regions drier.

A change in freshwater availability in response to climate change poses a more significant risk to human societies and ecosystems than warming alone. Fresh water regions are getting fresher and salty regions saltier in response to observed warming. The authors further suggest that the availability of fresh water for consumption, changes to the global water cycle and the corresponding redistribution of rainfall will affect food availability, stability, access and utilization.

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, 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.

Contemporary sea level rise. Cazenave A and Llovel W (2010). *Annual Review of Marine Science*, 2(1):145-173. http://dx.doi.org/10.1146/annurev-marine-120308-081105

Sea level observations have been reported from tide gauges over the twentieth century and from satellite measurements since the early 1990s. Such observations show clear evidence of global mean sea level rise, with regional variability. In this review, the authors present the most recent findings on sea level research, with most of the discussion concerning the last 50 years.

Sea level is currently rising, slightly faster since the early 1990s than during the previous decades. Approximately 30% of the rate of sea level rise is due to ocean thermal expansion in response to ocean warming. Mass loss in mountain glaciers and ice sheets accounts for approximately another 55%. Since 2003 ocean thermal expansion rate has slightly reduced while sea level has continued to rise. Estimates of land ice contribution indicate that ocean mass increase explains roughly 80% of the past 5-year observed sea level rate. If, as is most likely, the recent thermal expansion pause is temporary, and if land ice shrinking continues to accelerate, the prevailing sea level may increase more than expected in the near future.

Changes in salinity affect water density, which affects sea level. Freshwater addition to the oceans due to increased river runoff, precipitation, and ice melting modifies ocean salinity. The sparse coverage of salinity measurements for the past decades prevents reliable estimates of global mean ocean mass change by this method. With space data from GRACE (Gravity Recovery and Climate Experiment) satellites, it is now possible to directly estimate the change in global mean mass of the oceans. The authors note that the multidisciplinary aspects of sea level rise (observations, modeling, coastal impact studies) should remain a major area of future climate research.

Imprint of the El Niño Modoki on decadal sea level changes. Behera S and Yamagata T (2010). *Geophysical Research Letters*, 37(23):L23702. http://dx.doi.org/10.1029/2010GL045936

In addition to anthropogenic climate change and its influence on global sea level rise, modes of climate variation have been associated with spatial and temporal sea level changes. In particular, the El Niño/Southern Oscillation and Pacific Decadal Oscillation have been linked to regional sea-level variation occurring at annual to decadal time scales. In recent decades, a second type of El Niño has been observed in the central

Pacific, called the "El Niño Modoki" (or Central Pacific El Niño) arises. Classic El Niños are characterized by a maximum warm SST anomaly in the eastern Pacific. During the El Niño Modoki, the central Pacific exhibits a pattern of warm SST anomalies sandwiched between two cold anomalies. El Niño Modoki's counterpart is La Niña Modoki, when a colder central Pacific is flanked by warmer eastern and western Pacific. Wind patterns associated with El Niño Modoki (which differ from those associated with classic El Niño) cause sea level to rise in the central Pacific.

This study examines the decadal sea level changes associated with El Niño/La Niña Modoki. In order to understand the shifting of climate trends in the central Pacific in the recent decade, correlations were made between the central Pacific sea level index with anomalies of SST, surface winds and rainfall. Pacific Ocean sea level anomalies were derived from satellite data archived from late 1992 to 2010. Tide-gauge data from several stations were extracted from the Revised Local Reference data to measure sea level. Surface wind anomalies and SST and rainfall anomalies were also derived from climate datasets.

The authors found that the low frequency variability associated with El Niño Modoki has significantly influenced the decadal sea level anomalies of the tropical Pacific in the recent decade. From a phase of lower than normal sea level, associated with persistent La Niña Modoki conditions, wind convergences associated with frequent occurrences of El Niño Modokis appear to have given rise to higher than normal sea level in the central Pacific during the recent decade. These changes have influenced the decadal rise in sea level in distant regions such as the coasts of California and Hawaiian Islands.

City of Santa Barbara Sea-Level Rise Vulnerability Study. Griggs G and Russell N. (University of California, Santa Cruz) (2012). California Energy Commission. Publication number CEC-500-2012-039. http://www.energy.ca.gov/2012publications/CEC-500-2012-039/CEC-500-2012-039.pdf

This assessment of the vulnerability of the City of Santa Barbara to future sea-level rise and related coastal hazards is funded by the Public Interest Environmental Research (PIER) Program of the California Energy Commission. The study includes the development of a Guide for California's Coastal Communities about Adaption to Sea-Level Rise.

Sea level rose by about eight inches along California's coast over the past 100 years, but the relative rate of sea-level rise differs regionally. California's far north is the only place along the state's shoreline experiencing a sea-level drop relative to land surface, as sea-level rise is outpaced by coastal uplift. The effects of sea-level rise are exacerbated by El Niño occurrences and recent increases in the intensity of winter storms and wave heights.

The City of Santa Barbara coast features beaches, wetlands, housing, municipal infrastructure, and a commercial airport. Until about 2050, the combination of storm

waves with high tides is expected to continue to pose the greatest threat to the Santa Barbara coastline. Beyond 2050, a continuing rise in local sea level may lead to short-term flooding, permanent inundation of low-lying areas, and an increase in coastal erosion rates. The 6-12 inch per year historical average cliff retreat rate in the City of Santa Barbara translates to about 45-90 feet of cliff retreat by the year 2100, but areas are projected to retreat hundreds of feet with increased erosion rates. Historical data indicates tsunamis in the Santa Barbara area are low-frequency events with a low risk of damage, but may reach further inland as the sea level rises.

Santa Barbara exhibits a moderate ability to adapt to sea-level rise over the short to intermediate term (2012-2050), but low adaptive ability over the intermediate to long term (2050-2100). Local coastal adaptation strategies presented here focus on new and existing development, while the California Resources Agency outlines strategies for future policy and planning adaptations at the state level: (see http://resources.ca.gov/docs/climate/Statewide_Adaptation_Strategy.pdf)

Comparing climate projections to observations up to 2011. Rahmstorf S, et al. (2012). *Environmental Research Letters*, 7(4):044035. http://dx.doi.org/10.1088/1748-9326/7/4/044035

See summary under, *Changes in climate, Temperature*, page 80.

Causes for contemporary regional sea level changes. Stammer D, et al. (2013). *Annual Review of Marine Science*, 5:21-46. http://dx.doi.org/10.1146/annurev-marine-121211-172406

This review article summarizes regional aspects of sea level change and examines underlying mechanisms. The authors discuss the existence, importance, and implications of regional sea level changes, including trends and natural variability, as well as associated components and underlying processes. The discussion includes aspects of sea level caused by changes in ocean circulation as well as contributions from the Earth's response to past and present-day mass redistributions (e.g., due to land ice melt and land water storage changes) of either climatic or anthropogenic origin. Both observed and simulated (by numerical models) regional variability and trends are discussed. The authors emphasize contemporary regional sea level changes (covering the past few decades) as well as their causes and attribution to natural or anthropogenic processes.

The following are summary points from the article:

- Regional sea level changes can deviate substantially from those of the global mean, can vary on a broad range of timescales, and in some regions can even lead to a reversal of long-term global mean sea level trends.
- The underlying causes are associated with dynamic variations in the ocean circulation as part of climate modes of variability and with an isostatic (post-

glacial rebound) rise of land masses that were depressed by the Earth's crust to past and ongoing changes in polar ice masses and continental water storage.

- Relative to the coastline, sea level is also affected by processes such as earthquakes and anthropogenic induced subsidence of land. Present-day regional sea level changes appear to be caused primarily by natural climate variability.
- The imprint of anthropogenic effects on regional sea level will grow with time as climate change progresses, and toward the end of the twenty-first century, regional sea level patterns will be a superposition of climate variability modes and natural and anthropogenic induced static sea level patterns.
- Attribution and predictions of ongoing and future sea level changes require an expanded and sustained climate observing system.

Glaciers

Glaciers are one of the most visible indicators of climate change. With few exceptions, alpine glaciers—including those in the central and southern Sierra Nevada in California—have been receding globally in response to a warming climate over the past century.

Glacier variability in the conterminous United States during the twentieth century.
McCabe G and Fountain A (2013). *Climatic Change,* 116(3-4):565-577.
http://dx.doi.org/10.1007/s10584-012-0502-9

Glaciers have been receding in California's Sierra Nevada and throughout the Western U.S. for the past century. The rates of retreat were rapid in the early decades of the 20th century, slowed in the 1950s-1970s, and were rapid again in the 1990's. This paper examines changes in glacier area for 31 alpine glaciers in the U.S. (7 in California) during 1900 to 2000 to test a multi-step model that examines the effects of temperature and precipitation variability on these glacier area changes.

For each glacier, monthly air temperature and precipitation were used to calculate snow accumulation and snow melt values which were then used to estimate monthly snow water equivalent or SWE (amount of water contained in snowpack). A model was used to examine the relative contributions of temperature and precipitation on SWE estimates. To examine long-term glacier variability, decadal time series of glacier area change were developed using historical photographs and maps. The decadal time series were then used to test how well the SWE estimates the effects of temperature and precipitation variability on glacier area changes.

For most of the glaciers analyzed, the model results indicated a greater sensitivity to temperature variability than to precipitation variability. The glaciers most sensitive to precipitation variability, including the Sierra Nevada glaciers, are those located at high elevations. In these environments, winters are sufficiently cold, and historic warming of

winter air temperature does not affect the phase of the precipitation. Summer air temperatures, although warming, apparently do not influence the decadal variability as much as winter precipitation at high elevation sites.

Snowmelt 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. During the winter months, more precipitation will fall as rain instead of snow when temperatures are warmer. 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.

Observed climate-snowpack relationships in California and their implications for the future. Kapnick S and Hall A (2010). *Journal of Climate*, 23:3446-3456. http://dx.doi.org/10.1175/2010JCLI2903.1

Tracking the water content of snow (SWE) provides an understanding of how snowpack may be responding to a changing climate. Previous modeling studies show the Sierra Nevada snowpack has been declining and project a negative trend in SWE in the future. In this study, a metric is developed to calculate peak snow mass timing in the Sierra Nevada using SWE data from 1930 to 2008.

Monthly SWE from mid-January to mid-May was compiled for 154 stations across the state using two datasets (National Resources Conservation Service/Water Climate Center and the California Department of Water Resources). The monthly snapshots were used to calculate timing of *peak snow mass* for each snow season. Maximum and minimum daily temperature data from 1930 to 2003 were used to diagnose snow accumulation and melt processes.

Since 1930, there has been a trend toward earlier snow mass peak timing by 0.6 days per decade. Warm daily maximum temperatures averaged over March and April were associated with earlier peak timing for all spatial and temporal scales included in the dataset. This influence is likely due to the effect of early spring temperature on snowmelt. With projections of future warming in California, the relationship between March and April temperature and peak snow mass implies a continued trend toward earlier peak snow mass timing and potential impacts on the state's water supply, reservoir storage capacity and flood management.

Shifts in western North American snowmelt runoff regimes for the recent warm decades. Fritze H, et al. (2011). *Journal of Hydrometeorology,* 12(5):989-1006. http://dx.doi.org/10.1175/2011JHM1360.1

Regional climate is the dominant factor which determines the amount and timing of streamflow in natural river basins. The goal of this study was to establish whether and how streamflow timing for snowmelt-dominated, mixed, and rain-dominated regimes across the western North American region has responded to climatic drivers (spring warming, precipitation patterns). In particular, if the warming experienced through 2008 has resulted in either an acceleration of timing trends and/or a shift in the runoff regime (i.e., from snowmelt dominated to rain dominated).

The investigators analyzed changes in western North American streamflow timing over the years 1948–2008. They used linear trend analysis for different timing measures and correlated these changes to climate indices; developed an algorithm and classification method to distinguish between mostly snowmelt-dominated, mixed, and mostly rain-dominated basins; examined shifts in snowmelt-dominated regimes; and used models to determine whether an acceleration in streamflow timing changes has taken place. Basins were categorized by the percentage of snowmelt-derived runoff so that the authors could compare groups of streams with similar runoff characteristics and quantify shifts in snowmelt-dominated regimes.

Results indicate that streamflow has continued to shift to earlier in the water year, most notably for basins with the largest snowmelt runoff component. However, the authors could not determine the acceleration of streamflow timing changes for the recent warm decades. Most coastal rain-dominated and some interior basins have experienced later timing. The timing changes are connected to area-wide warmer temperatures, especially in March and January, and to subregional shifts in precipitation.

The most vulnerable basins have experienced runoff regime changes. Basins that were snowmelt dominated at the beginning of the observational period shifted to mostly rain dominated in later years. These vulnerable regions are located in the California Sierra Nevada, eastern Washington, Idaho, and northeastern New Mexico. This study provides further evidence that streamflow has responded to long-term changes in regional warming and precipitation, including streamflow in the most vulnerable basins. The authors note that snowmelt regime changes indicate that the time available for adaptation of water supply systems to climatic changes in vulnerable regions may be shorter than previously recognized.

The importance of warm season warming to Western U.S. streamflow changes. Das T, et al. (2011). *Geophysical Research Letters*, 38 (23):L23403. http://dx.doi.org/10.1029/2011GL049660.

Streamflow is likely to decline over much of the Western U.S., especially the Southwest, due to climate change. In this study, the authors used hydrological model simulations based on climate projections to examine how warm season warming can affect U.S. streamflow. The study area consisted of four regionally important river basins: the Upper Colorado; the Columbia; California's Northern Sierra Nevada; and California's Southern Sierra Nevada.

Simulations showed a substantial decrease in annual streamflow in response to warm season (April through September) warming: −13.3 percent, −7.2 percent, −1.8 percent, and −3.6 percent for a 3°C warming in the Colorado, Columbia, northern and southern Sierra basins, respectively. Cool season warming gives annual changes that are mostly much smaller: −3.5 percent, −1.7 percent, −2.1 percent, and −3.1 percent, respectively. Cool season warming stimulates greater streamflow immediately, which partly compensates for a subsequent decrease in summer streamflow that happens because less water is available. Summer warming stimulates greater evapotranspiration and diminished soil moisture immediately, with no process during the following winter that can generate a compensating streamflow increase.

In contrast to the substantial variability between the basins' annual streamflow response to a uniform year-round climate warming, the reduction in warm-season flow is projected to be much more consistent: −14.6 percent, −11.8 percent, −11.0 percent, and −14.3 percent in the Colorado, Columbia, northern and southern Sierra, respectively. The authors conclude that warm season warming has significant implications for annual runoff in the western U.S.

Streamflow response to climate as influenced by geology and elevation. Mayer TD and Naman SW (2011). *Journal of the American Water Resources Association*, 47(4):724-738. http://dx.doi.org/10.1111/j.1752-1688.2011.00537.x

This study investigates regional streamflow response to warmer winter temperatures and snowpack reductions over the last half century in 25 unregulated basins in the Klamath Basin of California and Oregon. There are two stream types in the basins: surface-dominated and groundwater-dominated. Based on elevation and timing of runoff, surface-dominated basins are further differentiated into rain basins and snowmelt basins.

Streamflow characteristics and response to climate vary with stream type. Warmer winter temperatures and snowpack reductions have caused earlier runoff peaks in both snowmelt and groundwater basins in the region. In the groundwater basins, streamflow response to changes in snowpack is smoothed and delayed and the effects last longer in the summer. Absolute decreases in July-September base flows are greater in groundwater basins compared to surface-dominated basins. Such declines are significant, since groundwater basins sustain Upper Klamath Lake inflows and main stem river flows during the usually dry summers in the area. Upper Klamath Lake April-

September net inflows have decreased by about 84 thousand acre-feet (an estimated 16 percent) since 1961, with summer months showing a larger decline.

The authors state that the changes observed in this study are expected to exacerbate water supply problems for agriculture and natural resources in the area. In addition, this study shows that not all streams respond similarly to climate.

Consequences of declining snow accumulation for water balance of mid-latitude dry regions. Schlaepfer D, Lauenroth W and Bradford B (2012). *Global Change Biology*, 18:1988-1997. http://dx.doi.org/10.1111/j.1365-2486.2012.02642.x

Decreases in snow accumulation and earlier snowmelt in the Northern Hemisphere have raised concerns about effects on ecosystem water balance. Changes in water balance dynamics are expected to be particularly pronounced at low elevations of mid-latitude regions that will be the first to be affected by declining snow due to warming temperatures. This study posed the question*: How sensitive are ecosystem water balance and vegetation activity to potential changes in snow associated with climate change scenarios, precipitation form and seasonality, vegetation phenology and snow melt-runoff?*

A simulation model (SOILWAT) was used to characterize water balance under future climate scenarios for ecosystems dominated by the common sagebrush, *Artemisia tridentate*. The authors examined 120 sagebrush sites in 11 western states stratified along a climatic gradient from dry, warm and snow-poor to wet, cold and snow-rich. About eight sites were located along the eastern side of the Sierra Nevada in California. The model used three climate scenarios: current for 1970-1999 and two future conditions for 2070-2099. Data incorporated by SOILWAT were daily weather, relative humidity, wind speed, cloud cover, monthly vegetation (e.g., live and dead biomass) and site-specific properties of soil. The analysis defined variables to describe snowpack, soil water flow, soil water quantity, soil water timing, and vegetation activity (e.g., transpiration rates).

The results identified the relative importance of factors influencing water balance. The analysis indicated precipitation seasonality and its interaction with vegetation phenology, followed by precipitation form (snow vs. rain), as the most important influences on water balance and vegetation activity. Snow melt-runoff was not an important water balance factor for mid-latitude dry regions where soils are unsaturated. It was concluded that ecosystems at low elevations respond in different and complex ways to future conditions because of opposing effects of increasing water-limitation and a longer snow-free season. According to the authors, these ecosystems will likely become drier and vegetation activity will decrease, especially at marginal areas near the southern limit of its range.

Causes of recent changes in western North American snowpack. Kapnick S and Hall A (2012). *Climate Dynamics*, 38 (9–10):1885-1899. http://dx.doi.org/10.1007/s00382-011-1089-y#page-1

An understanding of the basis for changes in the mountain snowpack over the last half-century is critical for developing adaptation strategies to avert water shortages or flooding. This study examines the mechanisms by which warming affects the temporal and geographical structure of changes in western North American mountain snowpack. Monthly SWE station observations (from 670 stations with at least 29 years of data in 12 western states) and gridded temperature data were used to analyze trends. The authors examined the interannual variability in snowpack and explored its relationship to monthly temperature during different phases of the snow season (February – May**).**

The analysis showed that during the earliest phase of the snow season (February), when temperatures are generally below freezing, temperature has little influence on snowpack, and February snowpack trends likely reflect snow accumulation. As temperatures rise significantly above freezing in March, inter-month SWE values decrease. During the mid to late period of the snow season (March through May), significant loss of snowpack occurred as a result of both decreases in snow accumulation and increases in snowmelt. The influence of late season temperature on the timing of the snowpack peak is evidenced by the earlier onset of snowmelt.

This study provides further evidence that recent snowpack changes in western North America are caused by regional-scale warming. In the future, the authors predict that continued warming in March and April will likely significantly shift the onset of melt earlier, reducing late season snowpack and summer snowmelt runoff.

The paradox of cooling streams in a warming world: Regional climate trends do not parallel variable local trends in stream temperature in the Pacific continental U.S. Arismendi I, et al. (2012). *Geophysical Research Letters*, 39(10):L10401. http://dx.doi.org/10.1029/2012GL051448

Temperature is a fundamentally important driver of ecosystem processes in streams. The authors examined correlations between stream flow temperature and air temperature at minimally and highly human-impacted (e.g., dams, water diversion and land use changes) watersheds located in California, Nevada, Oregon, Idaho, Washington, and Alaska. The authors used long-term stream gage records from the U.S. Geological Survey and U.S. Forest Service where stream temperature was monitored year-round. Air temperature data at the watersheds was collected from the University of Washington.

When the entire period of record was studied for the highly human-influenced sites, the authors found significant warming trends for minimum, maximum, and mean monthly stream temperatures. For more recent years (1987-2009), there were fewer warming trends and more cooling trends. Additionally, trends in variability of temperature for human-influenced sites decreased over time.

Historical trends in stream temperature for minimally human-influenced sites do not parallel trends in air temperature but were instead dependent on the length of the available time series. Consistent warming trends in the magnitude of stream temperature were more likely to be observed in sites with the longest records. Since 1987, there were more sites with available data, but there were more non-significant trends as expected with shorter time series. Where significant trends were detected, cooling of temperatures predominated. There were a limited number of minimally human-influenced sites whose time series represented at least 30 years. Collectively, these results highlight the importance of the duration and timing of a time series, as well as the limited representation of sites with minimally human-impacted for evaluating the effects of climate change on stream temperature.

Based on these findings, the authors concluded that the current perspective of climate impacts on stream temperatures is clouded by a lack of long-term data on minimally impacted streams, and inadequate existing time series. The authors highlight the need to develop more mechanistic, process-based understanding of linkages between climate change, other human impacts and stream temperature, and to obtain better information on trends in stream temperatures in the future.

Snowmelt runoff and water yield along elevation and temperature gradients in California's southern Sierra Nevada. Hunsaker CT, et al. (2012). *Journal of the American Water Resources Association*, 48(4):667-678. http://dx.doi.org/10.1111/j.1752-1688.2012.00641.x

The forested catchments (watersheds) of Sierra Nevada experience a range of seasonal changes that depend on winter and spring temperature and precipitation patterns. The lower end of this zone experiences rain more often than snow, with the upper elevations generally dominated by seasonal snow that undergoes spring melt over a relatively short period.

In this study, the authors set out to:

- Define the differences in hydrologic response across a 600-meter (m) elevation range involving a transition from a mixed rain-snow precipitation regime to a snow-dominated regime in eight catchments in the Kings River Experimental Watersheds
- Infer how future changes in temperature and forest density may affect that response.

Streamflow measurements (high, moderate, and low), temperature and precipitation data were analyzed. The authors found that small temperature differences between rain- vs. snow-dominated catchments result in significantly different timing of runoff and runoff ratios (i.e., discharge divided by precipitation) in Sierra Nevada mixed-conifer catchments. The approximately 600-m elevation difference in catchments results in daily maximum and daily average temperature differences of 3-4°C and 1-2°C,

respectively, and a 30-day difference in the timing of runoff. Thus, each 1°C increase in long-term average temperature could represent an earlier runoff in this zone of 7 to 10 days.

A longer growing season and more vegetation in the mixed rain-snow-dominated vs. higher-elevation snow-dominated catchments result in more evapotranspiration and canopy interception and thus lower water yield at the lower elevations. The authors conclude that both climate warming and forest management practices have the potential to significantly alter future hydrologic response of Sierra Nevada-forested catchments.

Searching for information in 133 years of California snowfall observations. Christy JR (2012). *Journal of Hydrometeorology*, 13(3):895-912. http://dx.doi.org/10.1175/JHM-D-11-040.1

See summary under *Changes in climate, Precipitation*, page 86.

Connecting physical watershed characteristics to climate sensitivity for California mountain streams. Stewart I (2013). *Climatic Change*, 116(1):133-148. http://dx.doi.org/10.1007/s10584-012-0567-5

California mountain streams provide critical water resources for human supplies and aquatic ecosystems, and have been affected by climatic changes to varying degrees. This paper presents a first attempt to identify and explain regional differences in stream sensitivity to climate change for the mountainous areas in California. Results from this study could facilitate prioritization of stream preservation efforts.

Sensitivity of streamflow timing of California mountain streams to trends in temperature and precipitation was examined for the years 1948-2009. The study also explored whether basin differences in the sensitivity of streamflow timing could be partially explained through the following physical characteristics of a watershed: elevation, slope, aspect (i.e., positioning), vegetation/land use, and geology. Only basins not affected by dams or diversions and with sufficiently long records were incorporated into the analysis. A special focus was placed on basins of Sierra Nevada and Klamath mountain areas of California, which are not significantly affected by damming, diversions, regulations, and inflows. These areas are also water-limited, heavily-drawn upon, ecologically sensitive and diverse hydrological systems.

Trends towards earlier runoff timing by several timing measures were observed throughout the mountainous regions of California and through the 2009 water year. The basins whose streamflow timing was most sensitive to climatic changes are on the western Sierra Nevada slopes. Watersheds on the eastern and southern Sierra Nevada and Klamath mountains exhibited little or no response to climatic shifts.

Basin sensitivity was linked to elevation. The most sensitive watersheds are located on the higher-elevation western Sierra Nevada slopes and are snowmelt-dominated. Large

basin-to-basin differences within close proximity in both runoff timing trends and sensitivity could be observed throughout the region, particularly for southern Sierra Nevada. Basin differences in sensitivity can be explained by differences in elevation ranges and combinations of physical watershed characteristics. The authors note that as warming and precipitation shifts continue, runoff amounts and patterns could be affected, impacting water supplies in this area.

The uneven response of different snow measures to human-induced climate warming. Pierce D and Cayan D. (2013). *Journal of Climate*, 26:4148-4167. http://dx.doi.org/10.1175/JCLI-D-12-00534.1

This study analyzes the effect of climate warming on different snow measures in the western U.S., including the Sierra Nevada, by calculating trends for the measures derived from regionally downscaled global climate models. The findings are based on analysis of climate change as represented by 13 models driven by two greenhouse gas and aerosol emissions scenarios known as RCP4.5 and RCP8.5. They are considered medium and high "growth" scenarios with CO_2-equivalent concentrations reaching about 800 ppm and 1300 ppm, respectively, by 2100. Downscaled model trends in several climate variables are presented relative to the 1976–2005 climatology for the high growth (RCP8.5) scenario.

What makes the study unique is their analysis of the "uneven" response of different snow measures to human-induced climate warming. This aspect of the study is important because it has implications for: (1) the detection of climate change and (2) planning by snow-sensitive groups. These snow measures include:

- *SWE*: The amount of water in the snowpack on 1 April
- *SWE/P*: The fraction of cold-season (1 October - 31 March) precipitation *P* that remains in the snowpack on 1 April.
- *Snowfall (SFE)*: The total cold-season snowfall measured as the amount of water in the snow.
- *SFE/P*: Fraction of total water in the cold-season precipitation that falls as snow.

The variables for which the long-term trend due to global warming emerges the earliest are temperature and the fraction of precipitation that falls as snow (SFE/P). In general, significant declining trends in SWE and snowfall emerge earlier and more strongly in regions with a warmer cold-season climate, including the Sierra Nevada. The authors note that there are important variations with region and elevation (i.e., for a given climate or snow variable, the “smoking gun” will emerge earlier in some regions and elevations and later in others). According to the authors, the accuracy of the analysis will depend on the models providing a reasonable projection of future climate change.

Impacts 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 community composition, and interfere with ecosystem functioning. This chapter summarizes publications on impacts on humans, animals and plants. Impacts on humans are categorized under heat-related morbidity and mortality, and other human health impacts. Impacts on animals are categorized as follows: range shifts; body size changes; migration time; population abundance and ecological interactions; and pathogens. Impacts on plants are categorized as follows: agricultural crops; vegetation; and wildfires.

Impacts on humans

Reports on climate-related impacts on humans tend to be focused on extreme events, notably heat waves and severe storms. Over the coming decades, average temperatures are predicted to rise and the number of days of summertime heat is projected to increase. Increases in the frequency and duration of heat waves are expected to result in a greater public health burden from heat-related mortality and morbidity. Other projected climate related health impacts include increases in vector-borne disease transmission; decreased food quality and security; increased death, disease and injury from storms, floods and fires; reduced water quality and availability; and increased morbidity and mortality associated with air pollution.

Research shows that future climate scenarios will disproportionately affect those who are socially and economically disadvantaged[2]. These groups include the urban poor,

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[2] Confalonieri, UB et al., *Human health. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. Posted at: http://www.ipcc.ch/publications_and_data/ar4/wg2/en/contents.html

Morello-Frosch, R., M. Pastor, J. Sadd and S.B. Shonkoff (May 2009). The Climate Gap: Inequalities in How Climate Change Hurts Americans and How to Close the Gap. -36-

children and the elderly, traditional societies, agricultural workers and rural populations. Some populations in California may already be experiencing greater impacts on their health or well-being as a result of climate change. This is addressed in a 2010 Cal/EPA report: "Indicators of Climate Change in California: Environmental Justice Impacts (see http://www.oehha.ca.gov/multimedia/epic/pdf/ClimateChangeEJ123110.pdf)

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. Recent literature also has focused on factors affecting vulnerability to the health impacts of climate change and indicators representing these factors that be used in vulnerability assessments.

High temperatures and health outcomes: A review of the literature. Martiello MA and Giacchi MV (2010). *Scandinavian Journal of Public Health*, 38(8):826-837. http://dx.doi.org/10.1177/1403494810377685

The goal of this paper is to analyze the relationship between high temperatures and population health impacts. The authors conducted a literature search for relevant papers available up to December 2009, and selected 113 studies on heat wave episodes, and on the relationship between temperature and mortality or morbidity for data analyses.

The paper lists 23 studies of mortality during heat waves in the United States and Europe. The studies provide evidence of excess mortality associated with heat waves. Although differences in the definition of a heat wave preclude direct comparisons of the estimated number of excess deaths across studies, the studies show that timing, intensity, duration and the lag effect are the most important factors associated with heat-related deaths. Two alternative hypotheses explaining the excess mortality—"mortality displacement" and the confounding (or modifying) effect of ozone pollution—were examined. Recent studies have demonstrated that mortality displacement (i.e., deaths occurring earlier among terminally ill individuals who would have died within a few weeks) account for a limited fraction (up to 15 percent) of the observed excess mortality) during major heat waves. The link between high temperatures and adverse health effects has been shown to be independent of air pollution in a growing body of evidence.

The authors reviewed 15 studies (from Australia, South America, Asia and the United States), and found the relationship between temperature and mortality to be a "V" shaped curve, with the excess risk occurring above a threshold. Multi-site studies

have shown that the threshold is usually higher in southern cities, indicating that residents of colder locations are more susceptible to high values of temperature.

Finally, the authors examined risk and protective factors. The reduction in heat sensitivity in the last decades was often explained by wider air conditioning usage, particularly in the United States. The most important risk factors are old age, pre-existing illnesses, low socioeconomic status, living alone, and living in the urban heat island. Health watch warning systems were identified as the most important and comprehensive public health response to counteract the adverse effects of extreme high temperatures. The authors note that the effectiveness of these systems needs to be evaluated.

Heat-related mortality: A review and exploration of heterogeneity. Hajat S and Kosatky T (2010). *Journal of Epidemiology and Community Health*, 64:753-760. http://dx.doi.org/10.1136/jech.2009.087999

Studies indicate that in many populations ambient heat affects mortality. Such effects occur in a range of geographical settings and at all levels of income. Using published estimates of population-level vulnerability to ambient temperature, this review paper reviews the heat-mortality relationship observed in cities throughout the world. The purpose was to explain between-city differences in risk in relation to a variety of climatic, demographic and socioeconomic parameters measured for each population.

The authors searched the databases MEDLINE (1950-present) and EMBASE (1974-present) for studies that included those conducted on multiple cities, that analyzed daily mortality and provided an estimate of the heat slope (increasing risk with temperature) and threshold (temperature value above which mortality risk begins to rise). Studies that analyzed only defined periods of exceptionally high temperature (heat waves), rather than general summertime heat, were excluded. Measures of climate, demography and economy were obtained from a wide variety of sources. For nine California counties identified in one study, city level information from representative cities was used.

Heat thresholds were generally higher in communities closer to the equator, suggesting some population adaptation. In almost half of the locations, the risk of mortality increased by between 1 percent and 3 percent per 18°C change in high temperature. Increasing population density, decreasing city gross domestic product and increasing percentage of people aged 65 or more were all independently associated with an increase in the heat slope. The authors concluded that improved care of older people and urban planning measures to reduce high temperatures are likely to play a key role alongside targeted heat-health warning systems in reducing future heat burdens.

A simple method for estimating excess mortality due to heat waves, as applied to the 2006 California heat wave. Hoshiko S, et al. (2010). *International Journal of Public Health*, 55(2):133-137. http://dx.doi.org/10.1007/s00038-009-0060-8

Data on the mortality impact of heat waves are needed to plan and evaluate the efficacy of public health interventions. However, analytic methods to estimate heat-associated deaths typically require specialized expertise and extensive data sources, complex statistical analysis and numerous years of temperature data–an analysis that is often beyond the capacity of health departments. This paper proposes a simple method by which excess mortality can be estimated, with the goal of developing an indicator for the mortality impact of heat-related climate change that could be adopted by state and other health departments.

Records of all deaths for June–August of 2006 were obtained from the Electronic Data Registration System files of the California Center for Health Statistics. The investigators selected July 15 through August 1 as the heat period (record-breaking heat occurred on July 15 to 26). To derive the expected number of deaths for the heat period, the investigators took the sum of deaths from an equivalent set of reference days close in time to this period. The number of deaths during the heat wave totaled 11,610, compared to an expected 10,955 deaths during the reference period, representing an estimated 655 excess deaths—a statistically significant increase of 6 percent deaths.

All regions of the state experienced excess heat wave-related mortality (although not all were statistically significant); hence, effects were not restricted to high heat regions. However, these findings did not track completely with morbidity outcomes. (For example, the Central Coast, despite the lowest mortality risk, experienced the highest excess of all regions for heat-related illness treated in hospital emergency rooms.) The reasons for these differences are beyond the scope of this study.

The findings of this analysis are supported by similar results using an alternative, broader reference period, as well as using more complex models used in the analyses of the 1995 Chicago heat wave. This simple approach to quantify health effects of heat events that is not dependent on elaborate statistical analyses or multi-year data may encourage more jurisdictions to conduct surveillance.

Health effects of hot weather: From awareness of risk factors to effective health protection. Hajat S, et al. (2010). *Lancet*, 375 9717):856-863. http://dx.doi.org/10.1016/S0140-6736(09)61711-6

As the health effects of hot weather are becoming a global public health challenge for the 21st century, cities across the world have introduced public health protection measures, most notably the timely provision of appropriate home-based prevention advice to the general public. In this review article, the authors report on epidemiologic and physiologic evidence of the health effects of hot weather, and examine the interplay among climate factors, human susceptibility, and adaptation measures in contributing to

heat burdens. Additionally, they review the evidence base for the most commonly offered advice about heat protection and make recommendations about the optimum clinical and public health practice for reducing heat-related health problems.

The human body's responses to the physiological effects of heat can be diminished or delayed in the elderly or other susceptible individuals (those with chronic illness or taking certain medication). Heat-related illness is generally underreported, as heat exposure is often not confirmed as the underlying cause of death. Heat exposure can contribute to the exacerbation of many pre-existing health conditions; in high-income countries, these are most commonly cardiovascular or respiratory causes.

Epidemiologic studies provide evidence of community level effects of heat, alone or in combination with high humidity, additional weather factors (such as air pressure, wind speed and cloud cover), or air pollution. The effects generally occur on the same day or within two days of initial exposure. In certain locations, 20 to 40 percent of deaths can be attributed to "mortality displacement," where heat hastens death mostly among already frail individuals; this percentage is likely to be smaller where the deaths are not restricted to chronically ill, elderly individuals, such as when a higher proportion of deaths arise from heatstroke in otherwise healthy individuals, or in low-income countries where deaths from infectious diseases might be common. Increases in emergency hospital admissions during hot weather are noted for renal disease, diabetes and mental disorders; in the United States, heart disease, acute myocardial infarction and congestive heart failure admissions increased, but not in Europe, where increases occurred among individuals with respiratory diseases. Routinely tracked metrics—such as ambulance transport, telephone helpline calls, dispatches by fire departments—may have some use for morbidity surveillance.

Risk factors associated with the highest risk of death during heatwaves were confinement in bed, pre-existing psychiatric illness, not leaving home every day, and inability to care for oneself. Mortality and morbidity rates are higher among the elderly and chronically ill individuals. The authors provide information on websites of 44 health-related or weather-related organizations that offer public guidance on heat protection, and noted that references were rarely provided for the recommendations; in some cases, websites provided contradictory recommendations. The authors listed the most commonly provided heat-protection advice to the general public (avoid drinking alcohol, wear lightweight clothing, drinking regularly, seek a cool environment, etc.). The authors give examples of advice that is supported by scientific evidence (e.g., increasing fluid intake, reduce activity levels) and advice that is not well supported (e.g., avoiding alcohol consumption, use of electric fans). The authors conclude that use of evidence-based health protection during hot weather by the general public and public health practitioners will have a key role in determining future heat burdens.

Climate change and health in cities: Impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. Harlan SL and Ruddell DM (2011). *Current Opinion in Environmental Sustainability*, 3(3):126-134. http://dx.doi.org/10.1016/j.cosust.2011.01.001

Excess morbidity and mortality related to extremely hot weather and poor air quality are found worldwide. The interactions of global climate change, urban heat islands, and air pollution are predicted to place increasing health burdens on cities. This review summarizes epidemiological studies between 2005 and 2010 that report on mortality and morbidity related to two climate hazards in cities: increasing temperatures and the modifying influence of air pollution.

Highlighted below are summary points discussed in further detail in the review:

- Excessive heat and air pollution increase mortality and morbidity in cities on six continents.
- There is a sense of urgency among public health professionals because future climate scenarios predict warming urban temperatures and increasing frequency and intensity of extreme heat events (EHEs).
- Identification of the most vulnerable populations and places is crucial because health burdens fall disproportionately on residents who are physiologically susceptible, socioeconomically disadvantaged, and live in the most degraded environments.
- Given the wide variation in local meteorology, level of pollutant emissions, capabilities of governments, and acclimatization of residents, the most 'actionable' research findings emerge from studies of specific cities.
- Risk management strategies for mitigating and adapting to climate change propose to reduce greenhouse gas emissions and achieve cooling through changes in the built environment, land use, and transportation. These changes could provide health co-benefits for residents, including reductions in heat-related and respiratory illnesses as well as 'lifestyle' diseases.
- Economic impediments to implementing costly aspects of city mitigation and adaptation plans require analysis of how health co-benefits can reduce the cost of mitigation and adaptation activities.

Heat waves in the United States: Mortality risk during heat waves and effect modification by heat wave characteristics in 43 U.S. communities. Anderson GB and Bell ML (2011). *Environmental Health Perspectives*, 119(2):210-218. http://dx.doi.org/ 10.1289/ehp.1002313

Heat waves are usually defined as extended periods of extreme heat, although no consistent definition exists regarding the temperature threshold, temperature metric, and number of days used to define heat waves. Although most studies use measures of intensity and duration to define a heat wave, few have investigated how these heat wave characteristics affect the mortality impact. The authors analyzed mortality risk for heat waves in 43 U.S. cities between 1987 and 2005 and investigated how effects relate to heat waves' intensity, duration or timing in season.

Daily non accidental mortality data for 108 U.S. urban communities were obtained from the National Morbidity, Mortality, and Air Pollution Study data set. Weather data came from the National Climatic Data Center. Heat waves were defined as greater than or equal to (≥) 2 days with temperature ≥ 95th percentile for the community from May 1 through September 30 and characterized by their intensity, duration, and timing in season. Within each community, the authors estimated mortality risk during each heat wave compared with non-heat wave days. Individual heat wave effect estimates were combined using modeling to generate overall effects at the community, regional, and national levels.

Nationally, mortality increased 3.74 percent during heat waves compared with non-heat wave days. Heat wave mortality risk increased 2.49 percent for every 1°fahrenheit (F) increase in heat wave intensity and 0.38 percent for every 1-day increase in heat wave duration. Mortality increased 5 percent during the first heat wave of the summer versus 2.65 percent during later heat waves, compared with non-heat wave days. Heat wave mortality impacts and effect modification by heat wave characteristics were more pronounced in the Northeast and Midwest than in the South.

The authors concluded that the observed heterogeneity, both in heat wave effects and in the influence of heat wave characteristics on mortality effects between different communities, indicates the importance of developing heat wave response plans that are community-specific.

A large change in temperature between neighboring days increases risk of mortality. Guo Y, et al. (2011). *PLOS ONE.*
http://dx.doi.org/10.1371/journal.pone.0016511

The frequency, intensity, duration of weather extremes, and unstable weather patterns are projected to increase with climate change. This study analyzed the relationship between day-to-day temperature change and mortality in summer, using statistical regression analysis and temperature data from Brisbane, Australia and Los Angeles, California. The cities were chosen for their sub-tropical climates and representation of both the Northern and Southern Hemispheres. Data collection included daily mean temperature, mean relative humidity, and non-external mortality (NEM) (e.g., not due to accidents, self-inflicted harm or other external means) for the summers of 1996-2004 in Brisbane, and 1987-2000 in Los Angeles.

In both cities, there was little effect on mortality when the temperature change ranged from -3ºcentigrade (˚C) to 3ºC. In Brisbane, a large drop in temperature between neighboring days increased the risk of total NEM, and NEM among those aged 65-74 years and in women overall. A sharp increase in temperature increased cardiovascular mortality and NEM among those aged <65 years. In Los Angeles, a large drop in temperature increased risk of total NEM, cardiovascular mortality, and NEM among those aged ≥75. Both cities exhibited joint effects of mean temperature and

temperature change on mortality. The authors note that while not necessarily generalizable to additional locations, the findings suggest large changes in temperature as well as absolute summer temperature should be considered when evaluating heat-related vulnerability.

Ambient temperature as a contributor to kidney stone formation: Implications of global warming. Fakheri RJ and Goldfarb DS (2011). *Kidney International*, 79(11):1178-1185. http://www.ncbi.nlm.nih.gov/pubmed/21451456

Nephrolithiasis (kidney stone formation) is a common disease that is becoming more prevalent worldwide. A body of literature suggests a role of heat and climate as significant risk factors. Recent estimates from computer models predicted up to a 10 percent increase in the prevalence rate in the next half century secondary to the effects of global warming. The authors critically review the medical literature relating stone formation to ambient temperature. They categorized the body of evidence by methodology, consisting of comparisons between geographic regions, comparisons over time, and comparisons between people in specialized environments.

The following are summary points discussed in further detail in the review:

- Although most studies are confounded by factors like sunlight exposure, genetic predisposition and regional variation in diet that may contribute to risk, it appears that heat does play a role in stone formation in certain populations. Notably, the role of heat is much greater in men than in women.
- Evidence supporting the role of temperature in the pathogenesis of stone disease has been seasonal variation with higher incidence rates during the warmer summer months than the colder winter months.
- Factors such as age, race, and socioeconomic background may potentially augment or mitigate an individual's sensitivity to the effect of climate.
- The role of a significant human migration from rural areas to warmer, urban locales may have a greater impact than global warming on the observed worldwide increasing prevalence rate of nephrolithiasis.

The authors conclude that evidence from global studies show that climate, whether it is through temperature, humidity, or sunlight, has at least some role in the development of kidney stones, in at least some patients. They note that the most consistently supportive data are the repeated demonstrations of seasonal variation in stone prevalence.

Social Vulnerability to Climate Change in California. Cooley H**,** et al. (2012). California Energy Commission. Publication Number CEC-500- 2012-013. http://www.energy.ca.gov/2012publications/CEC-500-2012-013/CEC-500-2012-013.pdf

California faces a range of impacts from climate change, and social vulnerability must be evaluated to understand how its populations will be affected. Social vulnerability is

defined as the susceptibility of a given population to harm from exposure to a hazard, affecting its ability to prepare, respond, and recover. Vulnerability is a function of demographic and socioeconomic factors, and low-income communities and communities of color are especially vulnerable to natural disasters. This analysis identifies geographic areas within the state at heightened risk of impact as a result of exposure and social vulnerability.

Nineteen vulnerability factors, including age, poverty, car ownership, fluency in English, and residential characteristics, were synthesized into a single vulnerability index, which was calculated for each census tract in the state. Very few tracts exhibited low vulnerability, while a disproportionate number of those with high vulnerability were located in Los Angeles County. In rural counties, highly vulnerable tracts represented a large fraction of the total population in the county. There were four primary drivers of social vulnerability: lacking a high school diploma, low income, non-English speaking, and people of color. These vulnerability indices were mapped and overlaid with projected changes in extreme heat, coastal flooding, wildfire, and air quality (associated with medium to medium-high greenhouse gas emission scenarios). The areas of overlap indicated areas with heightened risk of climate change impact.

Cold and heat waves in the United States. Barnett AG, et al. (2012). *Environmental Research*, 112:218-224. http://dx.doi.org/10.1016/j.envres.2011.12.010

Extreme cold and heat waves place a strain on people's cardiovascular and respiratory systems, and cause an the increase in deaths that may be greater than can be predicted by extreme temperatures alone. This paper examined whether the impacts of cold or hot days are heightened if they occur in sequence, whether cold or heat waves occurring earlier in the season caused greater health effects, and whether longer or more intense cold waves had a greater impact on mortality.

Using data on cold and heat waves in 99 United States cities for 14 years (1987–2000) from the National Morbidity and Mortality Air Pollution Study, the authors examined the associations between increased mortality risk and the temperature threshold used to define a cold or heat wave, its timing, duration and intensity. The authors defined cold and heat waves using temperatures above and below cold and heat thresholds—using the first to fifth percentiles of temperature for cold waves, and the 95 to 99th percentiles for heat waves—for two or more days.

The increases in deaths associated with cold waves were generally small and not statistically significant, and there was even evidence of a decreased risk during the coldest waves. Heat waves generally increased the risk of death, particularly for the hottest heat threshold. Cold waves of a colder intensity or longer duration were not more dangerous. Cold waves earlier in the cool season were more dangerous, as were heat waves earlier in the warm season. The oldest age group (age 75 and higher) had consistently larger increases in deaths associated with heat waves at all thresholds, and had the largest decrease in deaths at the coldest threshold.

In general there was no increased risk of death during cold waves above the known increased risk associated with cold temperatures. The authors noted that this may be because people take better protective measures during extreme cold waves, such as avoiding travel and wearing warm clothing. The same cannot be said for extreme heat, as the risks increased for the more extreme heat waves, suggesting that the public are less able to deal with extreme heat. Finally, the authors suggest that cold or heat waves earlier in the cool or warm season may be more dangerous because of a build-up in the susceptible pool or a lack of preparedness for extreme temperatures.

Impact of ambient temperature on children's health: A systematic review. Xu Z, et al. (2012). *Environmental Research*, 117:120-131.
http://dx.doi.org/10.1016/j.envres.2012.07.002

Despite increasing interest in assessing the impact of ambient temperature on children's health in a changing climate, no review has specifically focused on the relationship between temperature and children's health. This paper reviewed the literature regarding this topic and proposed future research directions. Empirical studies regarding the impact of ambient temperature on children's mortality and morbidity were included (children aged 0 to 18 years were the target population), and effect estimates (e.g., relative risks) were recorded.

Highlighted below are summary points discussed in further detail in this review:

- Physiological, metabolic and behavioral characteristics make children more sensitive to hot and cold temperatures than adults.
- Very young children, especially children under one year of age, are particularly vulnerable to heat-related deaths. Heat wave mortality varied across different countries.
- Evidence of cold-related mortality in children was found in a limited number of studies. No study on the relationship between cold temperature and cause-specific mortality was found.
- Hot and cold temperatures mainly affect cases of infectious diseases among children, including gastrointestinal diseases, malaria, hand, foot and mouth disease, and respiratory diseases.
- During heat waves, the incidences of renal disease, fever and electrolyte imbalance among children increase significantly.
- Pediatric allergic diseases, like eczema, are also sensitive to temperature extremes.
- The authors conclude that future research is needed to examine the balance between hot- and cold-temperature related mortality and morbidity among children; evaluate the impacts of cold spells on cause-specific mortality in children; identify the most sensitive temperature exposure and health outcomes to quantify the impact of temperature extremes on children; elucidate the possible modifiers of the temperature and children's health relationship; and project children's disease burden under different climate change scenarios.

Climate change and older Americans: State of the science. Gamble JL, et al. (2013). *Environmental Health Perspectives*, 121(1):15-22. http://dx.doi.org/10.1289/ehp.1205223

The proportion of older Americans (≥ 65 years of age) is projected to grow from the current 13 percent to 20 percent by 2040. At the same time, the rate of climate change—and its hazards associated hazards (such as rising temperatures, increased flood risk, droughts and wildfires)—is accelerating. This review article assesses the vulnerability of older Americans to climate change and to identify opportunities for adaptation. "Vulnerability" is the degree to which the ability of individuals or populations to cope with climate stressors is impaired; in this paper, vulnerability is considered a function of sensitivity, exposure and adaptive capacity.

Peer-reviewed papers and government reports dating from 2000 through 2011 were included in the literature review, as well as a number of earlier seminal articles. The paper discusses:

- factors that influence the vulnerability of older adults, specifically demographic factors (such as changes in socioeconomic characteristics, increased proportions of older (≥ age 65) and "very old (≥ age 85) due to increases in longevity and survivorship, and growing populations living in geographic locations likely to be increasingly affected by climate stressors) and physiological factors, such as respiratory, cardiovascular, diabetes-related and thermoregulatory impairments).
- climate stressors that may disproportionately affect older adults, including extreme heat, floods, droughts and poor air quality.
- factors that affect exposure to climate stressors, including socioeconomic characteristics (such as income, access to social and health services, and educational level), housing characteristics, the condition of infrastructure (such as telephone, gas, electricity and other utilities, and transportation), and availability of social services (such as local organizations, hospitals, governmental agencies).
- physiological and social factors that affect the degree to which older Americans—and the communities and services they depend on—can adapt to climate stressors (such as functional limitations and mobility impairments, economic status, living situation, and)access to communication tools and technologies.
- adaptation measures to reduce older Americans' vulnerability to climate extremes.
- research gaps for climate-related risks other than heat, and the interplay of vulnerability, resilience and adaptive responses to projected climate stressors among older adults.

Other human health impacts

In addition to mortality and illnesses resulting from exposure to heat, warming temperatures affect environmental conditions that can exacerbate certain illnesses. Changes in temperature and precipitation can alter the concentration of air pollutants and allergenic pollens and thus exacerbate asthma and other respiratory illnesses.

Warmer winters can shift the onset of the flu season, making it more difficult to immunize against influenza.

Urban air pollution and climate change as environmental risk factors of respiratory allergy: An update. D'Amato G, Cecchi L, et al. (2010). *Journal of Investigational Allergology and Clinical Immunology*, 20(2):95-102. http://www.allergy.org.gr/KJLMOLOI/wp-content/uploads/2013/02/11.pdf

Allergic respiratory disease and bronchial asthma are on the rise worldwide, affecting people living in urban areas more than in rural areas. This review article examines the evidence for the relationship between the development and exacerbation of asthma and air pollution in urban areas (specifically particulate matter, diesel exhaust particle, nitrogen dioxide and ozone) and discusses how climate change can alter the concentration and distribution of air pollutants and the seasonal presence of allergenic pollens in the atmosphere.

Particulate levels are associated with asthma exacerbations in children with persistent disease, but a link with the development of asthma is less well established. Fine particulate matter is considered a health risk, since it may be inhaled deeply into the lungs. Ozone induces epithelial damage and consequent inflammatory responses in the lung airways and high ozone levels are linked to acute and chronic asthma and asthmatic symptoms. Nitrogen dioxide is a pollutant that is less likely to induce airway inflammation.

The authors conclude that a changing climate may alter the incidence and prevalence of respiratory conditions. Ultraviolet radiation favors the formation of ozone, particularly in conditions like those observed in California. Global warming is expected to affect the start, duration, and intensity of the pollen season, as well as asthma exacerbations due to respiratory infections and cold air inhalation. Evidence exists that thunderstorms, a type of extreme weather event becoming more frequent, are associated with allergic asthma epidemics when the storm occurs during the pollen season. The role of pressure, temperature and humidity on the initiation and/or exacerbations of respiratory allergic symptoms remains poorly understood.

Effects of climatic changes and urban air pollution on the rising trends of respiratory allergy and asthma. D'Amato G (2011). *Multidisciplinary Respiratory Medicine,* 6:28-37. http://dx.doi.org/10.1186/2049-6958-6-1-28

This review article examines the evidence for the role of urban air pollution and climate change in the recent increase in respiratory allergies and asthma in most industrialized countries. Much of the article is devoted to discussing individual air pollutants (ozone, nitrogen dioxide, sulfur dioxide, particulate matter, diesel exhaust and plant-derived allergens) and studies that link them to asthma and other respiratory disorders.

The role of climatic factors (e.g., temperature and humidity) in triggering and/or exacerbating respiratory allergic symptoms in predisposed subjects was noted to be poorly understood. A variety of studies suggest that climate change may affect vegetation growth, reproduction and allergenic pollen release and consequently pollen-related asthma. For example, increased temperature in winter and spring can bring about early pollination, and increased summer temperature can result in a prolonging of the pollination of allergenic plants. Pollen seasons, and therefore seasonal allergic symptoms, tend to be longer in warmer years. Air pollution can affect plant growth as well as both the amount of pollen produced and the amount of allergenic proteins contained in pollen grains. The authors point out that genetic predisposition is an unlikely cause of the increasing frequency in allergic diseases because genetic changes in a population require several generations. Consequently, environmental factors such as climate change and air pollution may contribute to the increasing frequency of respiratory allergy and asthma.

Climate change and influenza: The likelihood of early and severe influenza seasons following warmer than average winters. Towers S, et al. (2013). *PLOS Currents Influenza*, Edition 1.
http://dx.doi.org/10.1371/currents.flu.3679b56a3a5313dc7c043fb944c6f138

The record mild 2011-2012 influenza season in the U.S. occurred during the fourth warmest winter on record. In contrast, the following influenza season (2012-2013) had an unusually early and severe start as indicated by laboratory-confirmed cases, despite the vaccine being a reasonably good match to the circulating strains. In addition, both influenza A and influenza B were off to an early start; in all previous years early epidemic seasons were due to the spread of one subtype only.

This article examines the relationships between influenza cases and winter temperature. The authors analyzed data on the “epidemic severity” (using “epidemic growth rate” as the metric) and time of onset of influenza for the 1997-1998 influenza season to present, and a population-weighted average winter temperature (January to March) and autumn temperature (September-December) for each year from 1997 to 2012 across U.S. regions.

Four pairs of correlations were analyzed: epidemic growth rate and epidemic peak timing were each correlated against the growth rate of the prior season and the average season temperature, also of the prior season. Significant associations were found, with similar patterns observed for both influenza strains. The influenza season following a mild winter was about 72 percent of the time more severe than average, exhibited a growth rate 40 percent higher than average, and peaked 11 days earlier than average. Influenza cases in such a season were 80 percent more likely to peak before January 1.

The researchers posit that fewer people are infected during warm winters, leaving a larger susceptible population the following influenza season. The severity of the latter season could be exacerbated by early onset, particularly if it occurs before extensive

vaccination has taken place. These results have implications for vaccine production and distribution in the influenza seasons following mild winters, which are expected to occur more frequently as a result of the changing climate.

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 (such as migration or egg-laying; known as "phenology"); changes in body size and other morphological features; and changes in population abundance. While some species will adapt to new climate conditions, not all will have the ability to respond to changes in climate. Extinctions will occur, current communities of species may disassemble as they respond differently to climate change and new species' assemblages will emerge.

The papers addressing impacts on animals are grouped below under headings that correspond to the responses listed above. Papers grouped based on whether they discuss terrestrial or aquatic impacts (a few papers cover both).

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 the poles or higher latitudes, or to higher elevations, are most commonly observed.

Range shifts: Terrestrial

Climate change and evolutionary adaptations at species' range margins. Hill JK, et al. (2011). *Annual Review of Entomology*, 56:143-159.
http://dx.doi.org/10.1146/annurev-ento-120709-144746

The authors review the impacts of climate warming on insect distributions, with a focus on evolutionary changes at the margins of species ranges. Three main aspects are covered; (1) current geographical patterns of genetic diversity and evolutionary

adaptations at range margins from postglacial (~12,000 years ago) range shifts; (2) evolutionary adaptations at recently expanding range margins; and (3) the implications of these adaptations for species' abilities to respond to future climate warming, and current knowledge gaps.

The following key points are discussed:

- Many insect species are responding to the current climate change and shifting their distributions to higher latitudes and altitudes. Evolutionary adaptations have been observed at the expanding high-altitude range margins.
- Recent range changes are similar to those during climate warming after the Last Glacial Maximum (~25,000 years ago), which resulted in latitudinal declines in genetic diversity from low to higher altitudes in many insect species and taxa.
- Declines in genetic diversity arise when colonization of new habitats is by a small number of individuals over long distances (attributable to a loss of alleles and reduced heterozygosity).
- Loss of genetic variation will likely continue as species spread across modern landscapes with heavily fragmented habitats.
- Evolutionary changes occur in populations at expanding range boundaries. Increased dispersal (reflected as morphological changes associated with flight, such as changes in wings and thorax) is the most commonly observed adaptation. Changes in habitat associations are also observed.
- There are trade-offs between flight and reproduction, such that range margin sites have individuals with reduced fecundity.

The authors noted that continued research will more fully elucidate the extent and speed of insect adaptation, which will provide a better understanding of how ecosystems and biodiversity can respond to climate change.

Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. Mantyka-Pringle CS, et al. (2011). *Global Change Biology*, 18(4):1239-1252. http://dx.doi.org/10.1111/j.1365-2486.2011.02593.x

Climate change and habitat loss are key processes threatening biodiversity around the world, yet little is known about their synergistic effects on biological populations. The authors present a meta-analysis of studies quantifying the effect of habitat loss on populations and examine whether climate conditions and historical rates of climate change affect the magnitude of these effects. The analysis is based on 1,125 papers from the past 20 years, addressing a range of taxa, geographic locations and climatic conditions.

Maximum temperature and precipitation change are the most important determinants of the negative effects of habitat loss and fragmentation on species density and/or diversity. Current maximum temperature was the most important determinant of the effects of habitat loss and fragmentation, followed by mean precipitation change over the last 100 years. Habitat loss and fragmentation effects were greatest in areas with

high temperature extremes (that is, where the maximum temperature of the warmest month was highest). Conversely, effects declined as mean precipitation increased over time.

To the authors' knowledge, this is the first study to conduct a global terrestrial analysis of existing data to quantify and test for interacting effects between climate and habitat loss on biological populations. Understanding the synergistic effects between climate change and other threatening processes has significant implications for conservation efforts.

Contrasting responses of *Peromyscus* mice of Yosemite National Park to recent climate change. Yang D-SC, et al. (2011). *Global Change Biology*, 17(8):2559-2566. http://dx.doi.org/10.1111/j.1365-2486.2011.02394.x

The authors investigated the response of two mice species (*Peromyscus maniculatus* and *Peromyscus truei*) to recent climate change in Yosemite National Park. *P. maniculatus* is a generalist species, and can thus thrive in a wide variety of environmental conditions. *P. truei* is a specialist species, and can thus only thrive in a narrow range of environmental conditions.

The generalist *P. maniculatus* did not change its distribution in response to climate change while the specialist *P. truei* significantly changed its geographic and elevational distribution. Genetic analyses indicated that a geographic shift in genetic variation may have occurred in the geographically stable *P. maniculatus* distribution. On the other hand, a *P. truei* subspecies expanded into new habitat types, suggesting that this subspecies is not a habitat specialist as previously thought. The shift upwards by 1032 meters suggests that recent climate change may have weakened a barrier to the subspecies' dispersal into high elevation habitats that were previously inhospitable. This expansion indicates that the subspecies is not specialized on pinyon-juniper vegetation, and is instead limited by climate parameters varying in response to contemporary climate change. According to the authors, this study highlights the importance of verifying assumptions used to develop predictive models of species' response to climate change.

Tracking of climatic niche boundaries under recent climate change. La Sorte FA and Jetz W (2012). *Journal of Animal Ecology*, 81(4):914-925. http://dx.doi.org/10.1111/j.1365-2656.2012.01958.x

In the past 30 years, global climate has changed, especially in northern temperate regions. Along with the poleward shifts in temperature regimes, there is evidence that some bird species have responded by moving their distributions to higher latitudes (in other words) by tracking their climatic niches. The term "niche" refers to the set of physical and biological conditions within which a species is able to persist. Determining how effective species are tracking their climatic niche is critical for improving the

predictive quality of modeling efforts and the conservation value of mitigation strategies. Current understanding of the distributional responses to rapid climate change is limited. This study provides a continental assessment of the temporal structure of species responses to recent geographic shifts in climate conditions.

The authors used survey data from the North American Christmas Bird Count for 59 winter bird species at 476 sites or "circles"(occurrences of bird species are determined within a 12-kilometer radius circle annually, a 24-hour period between December 14 and January 5) from 1975 to 2009. The lowest of the minimum winter temperature values measured in the circles where the species occurred in a given year was the climate variable selected for the analysis. Geographic associations between bird species occurrence and minimum winter temperature were assessed. Minimum winter temperatures associated with species occurrences increased overall from 1975 to 2009. Strong interannual variability was observed, with a lessened warming trend after 1998, and the largest warming gains at higher latitudes. Individual species' responses were variable and idiosyncratic; however, when considered in combination, species responded to warming temperatures by tracking minimum winter temperature.

Indirect evidence to date suggests that species do not move as fast as climatic trends and conserve as much of their niche as possible. There was a lag effect or delay in moving that persisted for about 35 years in direct association with a slowing or lull in the warming trend. There are limited geographic and ecological explanations for the observed variability, indicating that the efficiency of species' responses under climate change will vary and be difficult to predict. This outcome is likely to be even more pronounced and time lags more persistent for species with more limited dispersal abilities and strong regional habitat associations.

The idiosyncrasies of place: geographic variation in the climate-distribution relationships of the American pika. Jeffress MR, et al. (2013). *Ecological Applications,* 23(4):864-878. http://dx.doi.org/10.1890/12-0979.1

Many species are predicted to shift their ranges in response to global climate change, however unique combinations of factors relating to the environment, biota, and history can affect responses at local scales. This study explores how these factors—the "idiosyncracies of place"--affect the climate-distribution relationship of the American pika (*Ochotona princeps*), a species that has received considerable attention for its potential vulnerability to climate change in high-elevation ecosystems. The study specifically examined whether the patterns of American pika distribution covary with climate consistently across the species' range after accounting for local site characteristics.

The authors replicated intensive field surveys across bioclimatic gradients at randomly selected sites in eight United States national parks: Lava Beds National Monument and Lassen Volcanic National Park in California; Crater Lake National Park (in Oregon; Craters of the Moon National Monument and Preserve in Idaho; Grand Teton National Park in Wyoming; Rocky Mountain National Park and Great Sand Dunes National Park

and Preserve in Colorado; and Yellowstone National Park in Montana, Idaho, and Wyoming. Data from these replicated surveys were used to model pika site occurrence probabilities along regional bioclimatic and local topographic and vegetation gradients.

At the larger regional scale, the role of climate as a constraint on pika distribution appears unequivocal. The species, however, persists outside of its modeled bioclimatic area at many locations. After accounting for topographic position and vegetation cover—which influenced occurrence in all parks—the authors found that pika occurrence varied widely among parks along bioclimatic gradients.

- In four parks (rather than in all parks as would have been expected), measures of acute and chronic heat stress were negatively correlated with distribution patterns; low mean annual precipitation was a common characteristic in these four parks.
- In wetter parks, occurrence probabilities increased with heat and decreased with elevation. The anticipated relationship between extreme acute heat stress and pika distribution occurred only in the driest parks.
- While not alone a strong predictor of pika occurrence, precipitation had a strong mediating effect.
- Further, the combination of high elevation, cold temperatures, and high precipitation lowered occurrence probabilities in some parks, which suggests an upper elevation limit for pikas in some environments.

Cryptic loss of montane avian richness and high community turnover over 100 years. Tingley M and Beissinger SR (2013). *Ecology*, 94(3):598-609. http://dx.doi.org/10.1890/12-0928.1

Assessing change in species diversity (richness) is critical to understanding long-term community-level impacts of climate change. Current evidence for declines in species diversity due to climate change and long-term projections suggest that diversity will decrease along elevational gradients. In comparison, species turnover is predicted to be greatest at middle elevations, where low-elevation species should shift up and replace mid- to high-elevation species. The lack of uniform empirical observations on diversity may accurately reflect taxa- and region-specific differences in response to climate change, but they may also be partially due to sampling artifacts. In particular, imperfect detection of species can bias measures of diversity and community structure. This study uses unbiased estimators of species diversity that incorporate detectability to explore how bird species diversity and turnover have changed in California's Sierra Nevada with a century of climate change.

Species diversity was determined from survey sites distributed across three elevational regions that have seen significant climate warming over the last 80 years, especially during the avian breeding season in spring and summer. Sites were historical survey locations that were repeatedly visited from 1911-1929 by Joseph Grinnell from the University of California, Berkeley. Bird surveys from 77 sites were conducted between 2003 and 2009 as part of a systematic multi-taxon resurvey of the work by Grinnell and

others. Sites were located primarily in protected areas to minimize potential land use interactions. The authors used "occupancy modeling" to preserve species-specific and survey-specific detectability. By modeling species rather than diversity, they quantified both temporal turnover and diversity changes at three scales across resurveyed sites: (1) changes in total species diversity; (2) changes in diversity within elevational groupings of species; and (3) changes in occupancy of each species.

Bird communities along an elevational gradient in the Sierra Nevada showed a large degree of change over the last century. Per-site species diversity significantly declined over time; the average site lost only two species, but some sites lost up to 15 species. Sites experienced an average turnover of 35 percent of their species pool, indicating a high degree of underlying change in bird species composition.

Turnover in bird species composition over the past 100 years showed an unexpected relationship with elevation. Based on model projections, the greatest turnover was expected at middle elevations where species shifting upward with climate warming were expected to replace each other. Surprisingly, turnover in the study area was greatest at the lowest and highest elevations.

The authors conclude that the results provide empirical evidence for biodiversity loss in protected montane areas during the 20th century and highlight the importance of accounting for detectability in comparisons of species diversity over time.

Range shifts: Aquatic

Signature of ocean warming in global fisheries catch. Cheung WWL, et al. (2013). *Nature*, 497(7449):365-368. http://dx.doi.org/10.1038/nature12156

Marine species respond to warming temperatures in the ocean through distribution shifts, generally to higher latitudes and deeper waters. These shifts could impact fisheries through the 'tropicalization' of catch (that is, warm-water species become increasingly dominant). The authors present an index that represents the temperature preference of species in fisheries catch, called the *mean temperature of the catch* (MTC). MTC was calculated as the average of the inferred temperature preference of exploited species (990 species) weighted by their annual catch between 1970 and 2006, for 52 large marine ecosystems that account for most of the world's fisheries. The authors proposed that ocean warming leads to increased catches of warmer-water species and decreased catches of colder water species, resulting in an increase in the MTC.

Results showed that MTCs in the marine ecosystems increased at a rate of 0.19 ^{o}C per decade between 1970 and 2006, and non-tropical MTC increased at a rate of 0.23 ^{o}C per decade. MTC increased consistently in large marine ecosystems in the northeast Pacific Ocean (0.48^{o}C per decade) and the east Atlantic Ocean (0.49^{o}C per decade), where sea surface temperature increased by 0.20 and 0.26^{o}C per decade, respectively.

In tropical areas, MTC increased initially between 1970 and 1980 by around 0.6 ^{o}C per decade due to the reduction in proportion of subtropical species catches, and then stabilized at around 26 ^{o}C. Changes in MTC in the 52 large marine ecosystems, covering the majority of the world's coastal and shelf areas, are significantly and positively related to regional changes in sea surface temperature.

This study shows that ocean warming has affected global fisheries in the past four decades. The results suggest that change in the composition of marine fisheries catch is significantly related to temperature change in the ocean, with an increasing dominance of catches of warmer waters species at higher latitudes and a decrease in the proportion of catches of subtropical species in the tropics.

Range shifts: Aquatic and terrestrial

Adapt or disperse: understanding species persistence in a changing world. Berg MP, et al. (2010). *Global Change Biology*, 16(2):587-598. http://dx.doi.org/10.1111/j.1365-2486.2009.02014.x

Climate change is affecting the distribution of species and composition of communities around the world. Northward and westward migrations of species and advancement of phenology (that is, the timing of life cycle events) are attributed to rising temperatures. When species differ in their sensitivity to rising temperatures, mismatches in phenologies and dispersal patterns may occur. This results in disrupting interactions in an ecological community, such as mutualism, competition, predation and parasitism. In this review article, the authors discuss the importance of considering the ecology and evolution of multispecies interactions in elucidating the effects of climate change on ecosystems.

Simply scaling up the results of single species response to climate change is not sufficient to understanding its effects on community composition and stability, and ecosystem functioning. Instead, the authors propose a mechanistic approach that (a) first defines strategy groups (based on how the species deals with climate change (they either adapt or disperse); (b) then identifies the key species (that is, those involved in key interactions important for community stability and ecosystem functioning) and their interactions within these groups; and finally, (c) examines multispecies interactions involving selected traits. The authors propose two trait categories --thermal sensitivity of metabolic rate and associated life history traits, and dispersal traits. This approach, according to the researchers, would increase the feasibility of unraveling the large and diverse set of community interactions, with the ultimate goal of improving current understanding of community responses to global warming.

Community and ecosystem responses to recent climate change. Walther G-R (2010). *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1549):2019-2024. http://dx.doi.org/10.1098/rstb.2010.0021

This review article examines recent studies investigating how ecosystems and communities respond to climate change. The following topics are discussed:

- **Phenological changes and ecological networks.** The timing and synchrony of life-history events are influenced by the climate. Not all species in an ecosystem are equally responsive to climate and/or respond to the same environmental parameter. Such differences in response may lead to a mismatch in the timing of species interactions within ecological networks, such as food webs.

- **Species range shifts and community composition.** Changes in species ranges and distributions have occurred along altitudinal and latitudinal gradients. As with phenological changes, not all species are equally responsive. These changes can result in community reorganizations, impacting the way species interact, which has implications for ecosystem functioning.

- **Community reorganization and ecosystem responses.** The temporal and spatial changes induced by climate change are connected through interactions with other species at the same or adjacent tropic levels and beyond. Climate change influences community composition and ecosystem processes in concert with other drivers of global change. Community reorganization might not only lead to a reshuffling of existing species, but also add new species, creating new assemblages, thus contributing to modified ecological networks and altered ecosystem processes.

- **Increasing complexity through biotic interactions and feedback processes.** Recent research has shown an increasing number of 'fingerprints' of climate change. In addition, many species respond to climate changes with cascading effects through ecological networks such as food webs. This complexity makes it difficult to fully ascertain future impacts of climate change on communities and ecosystems.

The researchers conclude by stating that research should focus not just on individual organisms and species but also on the linkages between them. Ecosystems are complex and dynamic, with various thresholds and feedback processes, making it difficult to extrapolate ecological responses at the early stages of warming to future trends of climate change.

Novel communities from climate change. Lurgi M, et al. (2012). *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367(1605):2913-2922. http://dx.doi.org/10.1098/rstb.2012.0238

Novel communities with new combinations of species are emerging as a result of the changing biotic and abiotic conditions linked to climate change. Species responses to such changes reflect different degrees of adaptations and range shifts. The authors review the literature to examine whether certain traits determine species responses to climate change and, on that basis, what novel communities responding to climate change would look like. The review focused on two traits: body size, a commonly available surrogate of dispersal ability, reproduction timing and frequency, population abundance or metabolism, and ecological specialization. The authors explore how these traits predispose species to shift or expand their distribution ranges, and associated changes on community size structure, food web organization and dynamics. Their aim is to identify general patterns and major unknowns on the structure and dynamics of novel communities that emerge from climate change.

Three broad changes were identified:

- Shift in the distribution of body size towards smaller sizes
- Dominance of generalized interactions (some of which are newly established) and the loss of specialized interactions
- Changes in the balance of strong and weak interaction strengths in the short term—a change linked to the difference in size between predators and prey: the larger the difference, the larger their interaction strength.

The following uncertainties were identified:

- Whether large-bodied species tend to preferentially shift or expand their ranges more than small-bodied ones
- How interaction strengths will change over time and for newly interacting species

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Body size changes

Morphology can provide insight into the ability of species to respond to a changing environment. Changes in body size, a key physiological trait, in response to a warmer or increasingly variable climate have been reported. These changes may reflect both direct (e.g., temperature or precipitation outside the range of a species' physiological limits) and indirect (e.g., increased food availability) effects of climate change.

Declining body size: A third universal response to warming? Gardner JL, et al. (2011). *Trends in Ecology & Evolution*, 26(6):285-291. http://dx.doi.org/10.1016/j.tree.2011.03.005

There is a growing body of evidence linking climate change to observations of reduced body size in many species around the world. The authors discuss the evidence that body size reductions are a universal response to climate change (the other two being changes in phenology and distribution); progress in understanding the underlying mechanisms; and the potential for integrating historical data with metabolic theory and

biophysical ecology to identify the physiological and life-history consequences of size change.

Body size reductions have been reported from a growing number of species on multiple continents, for both endothermic (warm-blooded) and ectothermic (cold-blooded) species, and for both terrestrial and aquatic environments. Although the magnitude and direction of the size responses have been variable, the observations suggest a broad-scale physiological response to a major environmental change over the past 50 to 100 years, such as climate change. Because body size affects thermoregulation and energetics, changing body size has implications for resilience in the face of climate change.

Much of the evidence for size reductions are from studies of single species at individual locations or over short geographic distances; these likely reflect localized effects on body size and are less useful for defining broad-scale patterns. There is a need to establish whether size declines are universal across taxa or specific to particular ones, and whether the change relates specifically to temperature or to other environmental changes (such as food availability). Large scale comparative analyses of size change over time are needed to pinpoint the geographic, ecological and life-history factors associated with body size changes across groups of organisms.

The authors summarize by stating that understanding the mechanistic links between body size and environmental factors (such as climate and nutrition) will identify key traits important to a species' response to climate change. Integrative analyses of museum data combined with new theoretical models of size-dependent thermoregulatory and metabolic responses will increase both understanding of these underlying mechanisms and physiological consequences of size shifts and, therefore, the ability to predict the sensitivities of species to climate change.

Novel Communities from Climate Change. Lurgi M, et al. (2012). *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367(1605):2913-2922. http://dx.doi.org/10.1098/rstb.2012.0238

See summary under *Impacts on biological systems, Impacts on animals, Range shifts*, page 139.

Migration time

Biological processes are generally regulated by temperature, making them potentially sensitive to climate change. Long-term observations of seasonal biological events revealed some of the earliest evidence of how animals and plants are responding to changes in climate. Changes in the timing of life cycle events (also known as phenology) such as bird migration, butterfly emergence, and flowering, have been linked to climate change in many parts of the world. Many ecological interactions

among species (e.g., pollination) may be affected by phenological mismatches as a result of differences in species' responses to changes in climate, leading to community- or ecosystem-level disruptions.

Challenging claims in the study of migratory birds and climate change. Knudsen E, et al. (2011). *Biological Reviews*, 86(4):928-946. http:**//dx.doi.org/**10.1111/j.1469-185X.2011.00179.x

Birds have long been used as model organisms for studying the impacts of climate on animals, and changes in the timing of migration and breeding are among the best documented responses to climate change. The authors present claims and assumptions that have been made, discuss their basis and subjectively score their support and how much has been done to check their validity. The claims addressed fall under the following topics: changes in spring migration, mechanisms underlying observed changes, and consequences of climate change.

I. Changes in spring migration

Claim 1: Birds advance their spring migration in response to climate change.
Strong evidence supports this hypothesis, but there is much variability among species.

Claim 2: Phenological response to climate change depends on distance.
No firm patterns of different responses to climate change according to migratory distance can be established so far.

Claim 3: Climate change affects migration distance and routes.
While changes in spring arrival dates are often hypothesized as due to changes in the timing or speed of migration, range shifts and route changes may also be factors. Phenological consequences of migration patterns are little studied but may be important in light of range shifts predicted by climate models.

II. Mechanisms underlying observed changes

Claim 4: Mechanisms controlling the timing of migration are generally hardwired
Although there is strong evidence that bird migration is controlled by internal biological mechanisms in at least some species, it is not clear how rigid this control is in the wild. There is also evidence that, in addition to internal mechanisms, environmental conditions (such as food supply) may constrain migration timing.

Claim 5: Changes in the timing of migration are mainly due to phenotypic plasticity
Phenotypic plasticity is defined as the capacity an organism to exhibit different characteristics, without genetic changes, in response to environmental conditions.

Phenotypic plasticity is presumed to be the main mechanism behind recent changes in the timing of migration. However, there is also evidence that the changes in spring arrival may represent an evolutionary change, although the latter is hard to demonstrate. More research is needed to evaluate the relative importance of both evolutionary change and phenotypic adjustment.

Claim 6: Phenotypic variation in timing of arrival is mainly due to weather conditions* en route*.
Timing of arrival can be affected by weather conditions en route, but there are insufficient data to fully evaluate the relative magnitude of this effect for individuals, except for a few special cases.

Claim 7: Responses to climate change are constrained by the annual cycle
There has been increasing awareness of constraints imposed by the annual cycle on migration and arrival phenology. Such constraints relate to the interactions between the wintering, migration and breeding stages, where the effects of factors in one stage can affect the next. However, there is little empirical knowledge about how they affect migration timing in response to climate change.

III. Consequences of climate change

Claim 8: Migratory birds suffer from increased trophic mismatch on the breeding grounds
There are limited studies that a change in a bird species' migration time could mean arriving at the breeding grounds when food is not at its peak abundance.

Claim 9: Climate change causes population declines in migratory birds.
Climate change has been shown to affect population trends and is likely one important cause for current population declines. There is insufficient knowledge to demonstrate that populations of long-distance migrants are more vulnerable to climate change than populations of short-distance migrants or resident species.

Claim 10: Climate change affects community composition.
Climate change can affect the composition of breeding bird communities through range shifts and population trends. Habitat change and land use change have been demonstrated as factors that can confound climate change effects.

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 Niňo/Southern Oscillation and the Pacific Decadal Oscillation. Organisms may adapt to climate-related changes in temperature and water availability through the responses discussed earlier—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.

The linkages between climate change and population size, as well as interactions among species whose populations have been impacted by climate change are the subject of papers summarized in this section. Many of the papers that address marine population impacts present a multi-species or ecosystem-level discussion, rather than a single-species focus.

Does positioning of the North Pacific Current affect downstream ecosystem productivity? Sydeman WJ, et al. (2011). *Geophysical Research Letters*, 38(12):L12606. http://dx.doi.org/10.1029/2011GL047212

Fluctuations in the positioning of major ocean currents can influence ecosystem dynamics, but previously the technology has been lacking to make direct observational assessments. There is a hypothesis that positioning of the North Pacific Current (NPC) is related to biological attributes of the central- northern California Current Ecosystem. The Argo array (i.e., a global array of 3,000 free-drifting profiling floats that measure the temperature and salinity of the upper 2,000 meters of the ocean was used to study this hypothesis. Newly available data from the Argo array was compared with a suite of well-known ecosystem indicators over six years, 2002 through 2007.

The authors found increased biomass and productivity when the NPC was shifted poleward, and suggest that positioning influences fluid transport of nutrients and perhaps key planktonic organisms from the sub-arctic domain. Positioning shifts of the NPC would therefore enhance mid to upper trophic level species.

The authors noted that this study is significant because climate change is predicted to cause poleward shifts in the westerlies that drive ocean currents and positioning of large marine gyre systems. Rather than reducing ecosystem productivity, poleward shifts in positioning of the North Pacific Current may be beneficial for many species of the central-northern California Current Ecosystem.

Climate-driven trends and ecological implications of event-scale upwelling in the California Current System. Iles A, et al. (2011) *Global Change Biology,* 18(2):783-796. http://dx.doi.org/10.1111/j.1365-2486.2011.02567.x

Upwelling is projected to intensify as increasing greenhouse gas emissions warm land masses, creating a stronger thermal gradient between the warm land mass and cooler coastal oceans, thus driving more persistent upwelling-favorable winds. An important ecological consequence of upwelling is the delivery of nutrient-rich waters to the surface, causing blooms of phytoplankton that drive productivity of coastal ecosystems.

Alterations in upwelling events affect a wide range of ecological processes through changes in water temperature and chemistry and in the transport processes that influence species dispersal and recruitment. (Upwelling events are the time periods when the upwelling index is positive; the end of an event is marked by wind relaxation.) This paper examined long-term trends in upwelling events for Oregon and Northern California regions of the California Current System and associated these events with shellfish recruitment (number of young organisms added to adult population) at three sites along the Oregon coast. The investigators quantified trends in upwelling frequency, duration and strength over 43 years and related event-scale upwelling to water temperature and recruitment patterns of mussels and barnacles at the intertidal sites over the last 10-21 years.

The results showed that upwelling events are becoming less frequent, stronger and longer in duration and that longer events lead to colder near-shore temperatures. Mussels consistently responded positively as the duration of upwelling events increased, suggesting that recruitment will likely be positively affected by climate-driven increases in upwelling persistence. Barnacle recruitment tended to be more negatively related to the duration of upwelling. The authors suggest that these different responses may be related to the fact that mussel larvae are typically found below the thermocline layer and thus not susceptible to advection (transport processes) during upwelling, whereas barnacles are often found near the surface where these processes occur. The authors conclude that their results are consistent with predictions that altered upwelling events in offshore regions and are likely to significantly impact the structure and functioning of coastal ecosystems.

Drivers of change in estuarine-coastal ecosystems: Discoveries from four decades of study in San Francisco Bay. Cloern JEJ and AD Jassby (2012). *Reviews of Geophysics*, 50, RG4001. http://dx.doi.org/10.1029/2012RG000397

San Francisco Bay illustrates the rapid change occurring in many estuaries, bays, and inland seas in response to the diverse forces of the interface of rivers, ocean, atmosphere, and human settlements and to climate change.

Observations from the San Francisco Bay since the late 1960s where land and sea meet show responses to six drivers of change. These drivers are: water consumption and diversion, human modification of sediment supply, introduction of nonnative species, sewage input, environmental policy, and climatic shifts. In the San Francisco Bay, responses to these drivers include, respectively, shifts in the timing and extent of freshwater inflow and salinity intrusion, decreasing turbidity, restructuring of plankton communities, nutrient enrichment, elimination of hypoxia and reduced metal contamination of biota, and food web changes that lower resistance of the estuary to nutrient pollution.

Detection of these changes and discovery of their causes through environmental monitoring has been integral for establishing and measuring outcomes of environmental

policies that aim to maintain high water quality and sustain estuarine-coastal ecosystem services. The many time scales of variability and multiplicity of interacting drivers put heavy demands on estuarine monitoring programs, but the San Francisco Bay case study illustrates why the imperative for monitoring has never been greater.

Climate Change and Seabirds of the California Current and Pacific Islands Ecosystems: Observed and Potential Impacts and management implications. Final report to the US Fish and Wildlife Service, Region 1. Young L, et al. (2012). http://www.faralloninstitute.org/Publications/YoungEtal2012USFWSRep.pdf

The California Current ecosystem covers approximately 32,000 square kilometers ($km^{2)}$ of ocean habitat from British Columbia, Canada to Baja California, Mexico. Approximately 1-2 million seabirds representing 30 different species breed in the California Current. The Pacific Islands ecosystem includes the coastal and offshore areas of Hawaii and the U.S. Pacific Islands and atolls. The area encompassed by the Pacific Islands ecosystem is approximately 581,000,000 km^2. Approximately 10-12 million seabirds representing 30 different species breed in the Pacific Islands ecosystem.

Seabirds are marine animals which rely on the ocean for feeding and the land for breeding and may be particularly sensitive to the combined effect of climate change impacts on coastal and marine habitats. The purpose of this document is to review and evaluate how climate change may affect seabirds of the California Current and Pacific Islands ecosystems, with a focus on the effects of climate change on ocean processes and on seabird responses to oceanographic change.

Given the differences in oceanography between the California Current and Pacific Islands, it is likely that climate change will affect these systems and their seabirds in different ways; though some potential impacts could be similar. For example, the authors anticipate more severe impacts of sea level rise and ocean acidification on the Pacific Islands ecosystem and its low-lying terrestrial breeding sites for seabirds, which are more vulnerable than breeding sites in the California Current to coastal inundation and storm surges.

There are limited data available on how seabirds have already responded to climate change. Documented or hypothesized effects of climate change on California Current and Pacific Islands seabirds include:

- Inundation of breeding colonies from sea level rise and storm surge, especially for the many species using beaches, estuaries, or low-lying atolls in the Pacific Islands ecosystem, and for terns and gulls in the southern California Current.
- Reductions or changes in the horizontal and vertical distribution of food resources due to ocean warming and changes in winds. Species with restricted diets and foraging ranges will be most vulnerable.

- More variable demography (breeding success, survival, and recruitment) which could lead to population declines even if average rates of productivity remain constant.
- Northward redistribution of seabirds with changing winds and ocean structures thereby enhancing (or potentially initiating) breeding populations for species at the northern edge of their range and negatively affecting species at the southern edge of their range. This impact could be of equal importance in both ecosystems.
- Increased mortality with increases in heat stress (air temperature), storm intensity, or harmful algal blooms that can negatively affect seabirds through acute toxicity, immunosuppression, or various physiological effects. This impact could be similar between ecosystems.
- Potential decrease in foraging success in a suite of Pacific Islands seabirds resulting from changes in the abundance and distribution of tuna and other schooling, predatory fishes (which concentrate prey for these seabird species).

In addition to observed and potential impacts of climate change on seabirds in the Pacific regions, this report also discusses the following topics:

- The geographic scope and natural climate variability of North Pacific ecosystems
- Climate change factors for the California Current: atmospheric circulation, ocean warming and stratification, and ocean chemistry
- Potential climate change impacts on seabirds in the California Current
- Climate change factors for the Pacific Islands: atmospheric circulation, ocean warming and stratification, ocean chemistry, and prey availability

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Resilience to climate change in coastal marine ecosystems. Bernhardt JR and Leslie HM (2013). *Annual Review of Marine Medicine*, 5:371-392. http://dx.doi.org/10.1146/annurev-marine-121211-172411

Ecological resilience to climate change is a combination of resistance to increasingly frequent and severe disturbances, capacity for recovery and self-organization, and ability to adapt to new conditions. Diversity increases the variety of responses to disturbance and the likelihood that species can compensate for one another. Connectivity among species, populations, and ecosystems enhances capacity for recovery by providing materials that are used for propagating an organism to the next stage in their life cycle, nutrients, and biological legacies. Adaptive capacity includes a combination of an organism's phenotypic plasticity, species range shifts, and microevolution. The authors discuss empirical evidence for how these ecological and evolutionary mechanisms contribute to the resilience of coastal marine ecosystems following climate change–related disturbances, and how resource managers can apply this information to sustain these systems and the ecosystem services they provide.

Main points from the review article are highlighted below:

- Biological diversity plays an important role in enhancing resilience by increasing the likelihood that some species and/or functional groups will be resistant to perturbation.
- Multiple forms of connectivity (e.g., among species, populations, and ecosystems) can stabilize ecosystems under moderately fluctuating environmental conditions and enhance recovery following more severe disturbances.
- Adaptation to the changing climate will include a combination of organism-level plasticity, species range shifts, and rapid evolution of traits better suited to new conditions.

Ecosystem-based approaches to marine management and conservation, including those focused on resilience, emphasize the dynamic nature of ecosystem functioning—and human interactions within ecosystems—over time.

Further research is needed to address the following issues:

- The effects of diversity on community properties other than biomass and population abundance are largely unknown. Other related topics such as rates of nutrient cycling or bioturbation (the disturbance of the soil or sediment by living things).are important to study.
- Understanding of multiple forms of connectivity (from food web structure to the flow of materials among ecosystems) is limited. Testing theoretical predictions in real ecosystems is essential.
- Much remains to be learned about the relative importance of diversity, connectivity, and adaptive mechanisms in different marine systems. If the resilience framework is to effectively influence resource management, these elements must be investigated empirically in more systems and over longer timescales.
- Further understanding of the relative importance of phenotypic plasticity and genetic variation in generating adaptive capacity in real ecosystems could help guide future strategies to manage for ecological resilience.
- Assessment of Marine Protected Areas and other management and conservation strategies should include monitoring of ecosystem attributes related to diversity, connectivity, and adaptive capacity. Identifying specific indicators related to each of these resilience elements remains a key challenge.

Global imprint of climate change on marine life. Poloczanska ES, et al. (2013). *Nature Climate Change*, 3(10):919-925. http://dx.doi.org/10.1038/nclimate1958

A meta-analysis investigated the consistency of marine ecological observations with expectations under climate change. The analysis identified 1,735 marine biological responses for which either regional or global climate change was considered a driver. Included in the analysis were instances of marine taxa responding as expected in a manner inconsistent with expectations and taxa showing no response to climate change.

From the synthesis of studies used in the analysis, 81-83 percent of all observations for distribution, phenology, community composition, abundance, demography, and calcification across taxa and ocean basins were consistent with the expected impacts of climate change. Of the species responding to climate change, rates of distribution shifts were, on average, consistent with those required to track ocean surface temperature changes. No relationship was found between regional shifts in spring phenology and the seasonality of temperature. Rates of observed shifts in species' distributions and phenology are comparable to, or greater than, those for terrestrial systems.

The authors conclude that this study provides compelling evidence for widespread impacts of climate change in the ocean. A focus on understanding the mechanisms underlying the nature and magnitude of responses of climate change can help forecast impacts and costs to society and aid in adaptation and mitigation policies.

Increasing variance in North Pacific climate relates to unprecedented ecosystem variability off California. Sydeman WJ, et al. (2013). *Global Change Biology*, 19(6):1662-1675. http://dx.doi.org/10.1111/gcb.12165

There is significant evidence that along with the onset of human-caused global climate change comes increased ecosystem variability. However, studies of the impacts of climate change on ecosystems primarily focus on changes in central tendency rather than changes in variance. This study investigates how recent variability in populations of seabirds, salmon and rockfish in the California Current ecosystem (CCE) may be related to changing variability in regional upwelling and ocean circulation.

Recently, there have been signals of increasing variability in population dynamics of marine predators, including seabirds, salmon and rockfish in the CCE. For example, extreme fluctuations in the abundance of certain seabirds, such as the auklet, were observed in the early 2000s. Changes in "ocean climate" and prey availability are leading explanations for these notable population fluctuations in the North Pacific. Fundamentally, productivity in the CCE is determined by basin-scale oceanographic factors including localized regional *upwelling*—the vertical flux of cold, nutrient-laden waters that stimulates phytoplankton growth and food web development.

The authors examined whether the variability in salmon and seabird populations off California is related to increasing variability in remote, large-scale forcing in the North Pacific operating through changes in the food web. Data from ecosystem surveys performed by the National Marine Fisheries Service and others over the past three decades and indices of regional upwelling and selected of ocean phenomena known to influence North Pacific marine ecosystems were analyzed.

The results validate the claim that in the past two decades, the marine ecosystem of the North Pacific has seen an exceptional increase in variability. The abundance of krill and juvenile rockfish was associated with much of the recent variability in seabird and salmon populations. A strong connection was found between krill and the North Pacific

Gyre Oscillation index, but not regional upwelling. This suggests that remote, rather than regional mechanisms—possibly reflecting circulation and nutrient transport—are related to variability in the abundance of krill in the region. The authors note that it is challenging to determine the effects of climactic change on biological systems due to the complexity of climate-prey and predator-prey relationships. They further suggest that understanding this variability is essential to comprehending ecosystem dynamics and making informed policy choices that would lead to ultimate ecosystem health under a changing climate.

Relating spatial and temporal scales of climate and ocean variability to survival of Pacific Northwest Chinook salmon (*Oncorhynchus tshawytscha*). Sharma R, et al. (2013). *Fisheries Oceanography*, 22(1):14-31.
http://onlinelibrary.wiley.com/doi/10.1111/fog.12001/abstract

Pacific Northwest Chinook, *Oncorhynchus tshawytscha*, have exhibited a high degree of variability in smolt-to-adult survival over the past three decades. The variability of 22 Pacific Northwest stocks and Chinook survival trends from northern California to southeast Alaska were analyzed.

Results indicate that survival can be grouped into eight distinct regional clusters that are primarily geographically based. One such cluster covers the Klamath River and Columbia River Summers. Further analysis for stocks within each of the eight regions indicates that local ocean conditions—as characterized by SSTs—following the outmigration of smolts from freshwater to marine areas had a significant effect on survival for the majority of the stock groups analyzed.

This study provides evidence that survival of Chinook salmon stocks from the north California coast to southeast Alaska are affected by environmental conditions at ocean basin, regional, and local scales. The models presented are useful for projecting survival for Chinook salmon coastwide, and for developing a strategy that optimizes long-term sustainability of the resource. The SST–survival relationships identified in the study (if assumed to be indicative of a robust mechanism that will persist in a changing climate) can be used to infer the effect of climate change: a 1°centigrade (C) increase in SSTs during the key transition period (April through July) from freshwater to ocean environments could result in a reduction in Chinook survival of one to four percent across the species range.

Population abundance/ecological interactions: Aquatic and Terrestrial

Adapt or disperse: understanding species persistence in a changing world. Berg MP, et al. (2010). *Global Change Biology*, 16(2):587-598.
http://dx.doi.org/10.1111/j.1365-2486.2009.02014.x

See summary under *Impacts on biological systems, Impacts on animals, Range Shifts*, page 138.

Community and ecosystem responses to recent climate change. Walther G-R (2010). *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1549):2019-2024. http://dx.doi.org/10.1098/rstb.2010.0021

See summary under *Impacts on biological systems, Impacts on animals, Range Shifts*, page 139.

Novel communities from climate change. Lurgi M, et al. (2012). *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367(1605):2913-2922. http://dx.doi.org/10.1098/rstb.2012.0238

See summary under *Impacts on biological systems, Impacts on animals, Range Shifts*, page 139.

Vulnerability of riparian ecosystems to elevated CO_2 and climate change in arid and semiarid western North America. Perry LG, et al. (2012). *Global Change Biology*, 18(3):821-842. http://dx.doi.org/10.1111/j.1365-2486.2011.02588.x

Riparian ecosystems, already greatly altered by water management, land development, and biological invasion, are being further altered by increasing atmospheric CO_2 concentrations and climate change, particularly in arid and semiarid (dryland) regions. In this literature review, the authors (1) summarize expected changes in CO_2 concentrations, climate, hydrology, and water management in dryland western North America, (2) consider likely effects of those changes on riparian ecosystems, and (3) identify critical knowledge gaps. Highlighted below are summary points from the article:

- Temperatures in the region are rising and droughts are becoming more frequent and intense. Warmer temperatures in turn are altering river hydrology: advancing the timing of spring snowmelt floods, altering flood magnitudes, and reducing summer and base flows.
- Direct effects of increased CO_2 concentrations and climate change on riparian ecosystems may be similar to effects in uplands, including increased heat and water stress, altered phenology and species geographic distributions, and disrupted trophic and symbiotic interactions.
- Indirect effects due to climate-driven changes in streamflow may exacerbate the direct effects of warming and increase the relative importance of moisture and fluvial disturbance as drivers of riparian ecosystem response to global change.

- Together, climate change and climate-driven changes in streamflow are likely to reduce abundance of dominant, native, early-successional tree species; favor herbaceous species and both drought-tolerant and late-successional woody species (including many introduced species); reduce habitat quality for many riparian animals; and slow litter decomposition and nutrient cycling.
- Climate-driven changes in human water demand and associated water management may intensify these effects. On some regulated rivers, however, reservoir releases could be managed to protect riparian ecosystem.
- Immediate research priorities include determining riparian species' environmental requirements and monitoring riparian ecosystems to allow rapid detection and response to undesirable ecological change.

Trends in the surface chlorophyll of the California Current: Merging data from multiple ocean color satellites. Kahru M, et al. (2012). *Satellite Oceanography and Climate Change*, 77-80:89-98. http://dx.doi.org/10.1016/j.dsr2.2012.04.007

Oceanic phytoplankton plays an important role in global carbon and energy budgets and any changes in its composition and/or concentration are of interest in the context of climate change. While the primary expected response to increased surface warming of the ocean is increased stratification and decreased primary productivity, studies in the California Current have reported the opposite trends: increasing turbidity and increasing surface chlorophyll-a (Chl-a) and primary productivity in the coastal zone. The complex interactions between surface warming and wind forcing and upwelling are difficult to predict and are the subject of this study.

The authors use a 15-year record of data taken from the California Current to study trends in surface Chl-a. Standard remote sensing reflectance products from four ocean color sensors (OCTS, SeaWiFS, MODISA, MERIS) and over 10,000 in situ measurements of Chl-a concentration in the California Current were used to create empirical algorithms that are consistent with *in situ* data as well as between individual sensors.

The algorithms show multi-decadal trends in chlorophyll that are not simply artifacts of sensor design or processing methodology. Using these algorithms, a merged multi-sensor time series of the surface Chl-a concentration in California Current region was created. This analysis is an important first step towards creating Climate Data Records for coastal waters such as the southern California Current System.

The merged Chl-a time series (November 1996–December 2011) show a significant ($P<0.01$) increasing trend off central California and significant ($P<0.01$) decreasing trends in the central North Pacific gyre and off southern Baja California. Although this 15-year time series is too short to separate interannual and multidecadal cycles from climate trends, both of these trends are consistent with the predicted effects of global warming. The expected increase in vertical stratification of the water column and the resulting decreased vertical flux of nutrients would lead to lower Chl-a in the gyre but

the increased upwelling-favorable winds leading to stronger upwelling off central California or the increased nitrate content of the upwelled water would lead to higher Chl-a in the upwelling region. The decreased Chl-a off southern Baja California resembles the effect of a decreased influence of strong El Niňo events.

Pathogens

Pathogens are disease-causing infectious agents, and include viruses, bacteria, and parasites. Pathogens infect a wide variety of hosts, such as humans, animals, plants, fungi, and even other microorganisms. Climate change can directly impact the distribution, life cycle, and physiological status of hosts, pathogens, and vectors. An emerging body of literature focuses on the influence of climate change on the spread of infectious disease.

Climate change increases the risk of malaria in birds. Garamszegi LZ (2010). *Global Change Biology*, 17(5):1751-1759. http://dx.doi.org/10.1111/j.1365-2486.2010.02346.x

Malaria, caused by Plasmodium parasites, is a major disease around the world and threatens wild animal populations. Climate change is hypothesized to enhance the transmission and reproduction of the parasite. In this study, the author tested for the link between climate change and malaria prevalence on a global scale using long-term records on avian malaria (a key model for studying the dynamics of naturally occurring malarial infections). Data on the prevalence of Plasmodium for over 3,000 bird species over seven decades were extracted from published studies; temperature data for the geographic coordinates and time span of the selected studies were used in the analysis.

The infection rate by Plasmodium was found to be strongly and positively associated with temperature anomalies: a 1°C increase in global temperatures was accompanied by a two- to three-fold increase in the average prevalence of malaria in birds. The impact of climate change on malaria prevalence varies across continents, with the strongest effects found for Europe and Africa. Migration did not have a significant effect on infection prevalence.

Climate change and microbiological water quality at California beaches. Semenza JC, et al. (2012). *EcoHealth*, 9(3):293-297. http://dx.doi.org/10.1007/s10393-012-0779-1

This study examines whether changes in precipitation patterns under climate change scenarios will result in improved recreational water quality at beaches in southern California. Precipitation events are an important driver for contamination of coastal water, as rainwater can carry bacteria from numerous sources through stormwater systems, often discharging untreated runoff into coastal waters. Exposure to elevated

concentrations of bacteria such as *Enterococcus* in bathing waters has been linked with an increased risk of contracting infectious diseases, such as gastroenteritis.

Climate models project that California will become hotter and drier through the twenty-first century and that southern California will experience a decline in total annual precipitation between 4 and 16 percent, with the decline occurring mainly during the wet season. However, the infectious disease burden peaks during the summer months when 53 percent of beach visits occur, in spite of lower bacteria contamination levels compared to winter months.

Daily microbiological water quality and precipitation data spanning six years were collected from monitoring stations at 78 beaches in Orange, Los Angeles and San Diego counties. Daily precipitation projected for the twenty-first century was derived and downscaled from a global climate model. Projected precipitation was used in a model to predict daily *Enterococcus* water contamination levels for the beaches throughout the 21st century. The modeled projections matched well with empirical water quality data. The study found a positive association between precipitation and microbiological water contamination ($p < 0.001$). Future projections of less precipitation result in a decrease in predicted *Enterococcus* levels through the majority of the twenty-first century. According to the researchers, the resultant effect of these projected changes on disease burden, however, is currently difficult to accurately predict.

Climate change impact assessment of food- and waterborne diseases. Semenza JC, et al. (2012). *Critical Reviews in Environmental Science and Technology*, 42(8):857-890. http://dx.doi.org/10.1080/10643389.2010.534706

Climatic conditions can influence the fate and transport of pathogens, as well as their viability, stability, and reproduction rates in the environment. Projected changes in precipitation, ambient temperature, and extreme precipitation or temperature events will directly affect exposure pathways of food- and waterborne diseases. In this review, common terms and an electronic knowledge base were used to create semantic network maps (knowledge mapping) and evaluate the impact of a changing climate on trends in campylobacteriosis, cryptosporidiosis, listeriosis, and salmonellosis from 1995 to 2007. Although the article examined disease and temporal distribution data for Europe, its findings on the association between environmental determinants and food- and waterborne diseases are relevant elsewhere.

Campylobacter: The incidence of campylobacteriosis displays strong seasonality, with increased incidence linked to higher ambient temperatures and relatively low humidity after a lag of 2-3 weeks. The principal reservoir is the alimentary tract of animals, and meat, raw milk, and fresh vegetables can easily be contaminated. Rising temperatures will increase the prevalence in animals and increase the risk of human infection if cooling throughout the food chain is not addressed. Outbreaks are triggered by heavy rain events, especially when preceded by a period of drought. Changing use patterns of private water sources may put humans and animals increasingly at risk.

Salmonella: Salmonellosis infection patterns are seasonal, with a peak in late summer. Ambient temperature increases are suspected drivers of about 30 percent of salmonellosis cases. Heavy rainfall may disrupt water treatment and sewage systems, increasing exposure, yet health promotion and food safety policies should be able to mitigate negative impacts on human health.

Cryptosporidium: The waterborne protozoan parasites exhibit seasonality, but the peaks occur at different times between spring and fall. Heavy rainfall, and the subsequent surface runoff and resuspension of sediment, have been associated with water contamination and cryptosporidiosis outbreaks. Increases in rainfall and extreme precipitation events, as well as warmer winter temperatures, may increase cryptosporidiosis risks to humans.

Listeria: Seasonal trends are weak; species are ubiquitous in the environment and can be found worldwide. The changing climate is unlikely to affect the occurrence of *Listeria* sp. in their habitat, but could lead to more cases via indirect pathways.

Norovirus: Norovirus exhibits seasonality with a typical peak in the winter in the northern hemisphere, which is not mirrored in the southern hemisphere. Climate does not seem to be the main determinant. Floods are linked with Norovirus outbreaks.

Noncholera vibrio: The organism is waterborne with a summer peak; elevated mean temperatures increase growth opportunities in bodies of water. In hot climates, the minimum temperature was the primary factor contributing to growth. Rising summer temperatures and longer summer season are linked to infections, but the increase in disease burden is expected to be modest.

The approach used here to catalogue, quantify, and assess the present state of knowledge in this area exposed a number of data gaps, even as associations between weather events and measurements have been linked to these pathogens. The authors noted that data gaps should be filled, and surveillance systems installed to monitor the environmental precursors of epidemics.

Impacts on plants

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

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, CO_2 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.

Currently, there is little evidence of the observed impacts of climate change on agricultural crops. This may be due to non-climate factors, particularly management practices and technological improvements designed to maximize productivity.

Varying temporal and spatial effects of climate on maize and soybean affect yield prediction. Sakurai G, et al. (2011). *Climate Research*, 49(2):143-154. http://dx.doi.org/10.3354/cr01027

Mounting evidence from changing global climate and precipitation patterns indicates that the future of food security could be threatened. Researchers are estimating potential effects of climatic factors such as temperature and precipitation on crop yields. During the last quarter century, agricultural techniques, such as specialized crop cultivars and irrigation systems, have changed dramatically. Thus, when analyzing the effects of climate change on crop production, methods that consider temporal changes in the relationship between weather and crop yields should be used.

The authors statistically estimated the time-series changes in the relationship between climatic factors and crop yields for a large area (1.125° × 1.125° latitude by longitude) using a data assimilation method known as “particle filtering”. The staple target crops maize and soybeans were studied in three major producing countries: the United States, Brazil, and China. Temperature and precipitation data were obtained from the Japanese Re-Analysis dataset, which covers regions across the globe using a grid scale. Crop yields were estimated for each grid point by averaging the yield data of the counties included in the grid. Based on the analysis, maps of the ‘current’ effects of weather on crop yields were generated. To evaluate the effect of temporal variations on the relationship between weather and crop yields in estimations of future productivity, the authors compared the effect on crop yields as estimated by the ‘past’ relationship between weather and crop yields with the effect estimated by the ‘current’ relationship.

The most important finding was that there were significant temporal changes in the effect of climate on crop yields in many regions. In previous studies, the relationships between climatic factors and crop yields were assumed to be constant over time. In the

U.S., on average, crops were more affected by temperature than by precipitation during the last quarter of a century. In Brazil, crops were more affected by precipitation; this difference could be explained by the prevalence of irrigation systems. According to the authors, the effect of the climatic factors significantly changed throughout the time series, suggesting that methods that account for temporal variations in parameters, such as the particle filtering method, are needed to evaluate and estimate the future impact of climatic factors on crop yields.

Detecting nonlinear response of spring phenology to climate change by Bayesian analysis. Pope KS, et al. (2013). *Global Change Biology*, 19(5):1518-1525. http://dx.doi.org/ 10.1111/gcb.12130

The impact of a warming climate on the advancement of plant phenology has been increasingly studied in the past decade. Although most spring plant phenological events (e.g., budding, blooming) are trending earlier, there are exceptions. Recent work has indicated that fruit and nut species not advancing in their spring phenological behavior are responding more to lack of winter chill hours (i.e., temperatures below 45 degrees Fahrenheit) than to increased spring heat. To test this hypothesis, the authors evaluated the behavior of a species known to have a moderate to high chilling requirement and examined how it is responding to increased warming.

The authors investigated whether chill accumulation in California's Central Valley has decreased to a level that is suboptimal for walnuts. If such were the case, later spring phenological behaviors would be observed in more recent years when chilling has been substantially reduced. A 60-year dataset for timing of leaf-out and male flowering of walnut (*Juglans regia*) cultivar 'Payne' was used. The data record came from an observational site on California's UC Davis campus. Minimum temperature records from the Davis site showed temperatures increased significantly from 1957 to 1975, with increases becoming highly significant from 1978 to 2006. Maximum temperature records showed a highly significant trend starting in 1986. *Bayesian change point analysis* (i.e., multiple change points compared in six different models) was used to detect whether plant phenology has responded to increased temperatures over several decades.

The walnut studied responded to recent warming with two very different phenological behaviors. There was a trend toward earlier leaf-out until approximately 1994, and subsequently leaf-out started coming later, with a much steeper slope than the initial earliness. However, the date of male flowering over the 60-year period only advanced. This study is the first reported case of a spring phenology record (leaf-out) for a species getting earlier, and then later. These results support experimental evidence that the temperature response of spring phenological timing is not linear. It is noted that not all walnut species have shown this dual response (advancing and then delaying) in bud behavior. The disparate results could be attributed to differences in climate and among cultivars.

The authors conclude that the climate has been changing in the Central Valley of California and that the phenological behavior of some plants (or organs of plants) has changed with it. They further suggest that for some varieties of walnuts and other varieties of species with high chilling requirements, the Central Valley may be shifting toward being an unsuitable area for cultivation and growth.

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.

A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Allen CD, et al. (2010). *Forest Ecology and Management*, 259(4):660-684. http://dx.doi.org/10.1016/j.foreco.2009.09.001

The effects of climate change on forests include both positive (e.g., increases in forest vigor and growth from CO_2 and longer growing seasons) and negative effects (e.g., reduced growth and increases in stress and mortality due to the combined impacts of climate change and the related dynamics of forest insects and pathogens). This review article provides an overview of the literature reporting tree mortality attributed to drought and warm temperatures in forests around the globe. The authors explore the hypothesis that forests are becoming more susceptible to higher background tree mortality rates and die-off in response to increased warming and drought.

Eighty-eight examples of forest mortality were identified that were driven by climatic water and heat stress since 1970. The examples range from modest but significant local increases in background tree mortality rates to climate-driven episodes of regional-scale forest die-off. Climate-induced tree mortality and forest die-off is relatively well documented for North America. Drought and elevated temperatures across western North America in the last decade have led to extensive insect outbreaks and mortality in many forest types throughout the region. In California, multiple tree mortality events were identified since the 1980s that were associated with drought and high temperatures. Tree mortality in other regions around the world, including areas in eastern North America, Africa, Australia, Europe, and Central and South America are also discussed.

This overview illustrates the complex impacts of drought and heat stress in patterns of tree mortality, and hints at how changes in drought and/or heat stress can lead to increasing background tree mortality rates and rapid die-off events. The examples suggest that no forest type is invulnerable to climate change, even in environments not

normally considered water-limited. The authors note that although the effects of climate change cannot be isolated in these studies and episodic forest tree mortality occurs in the absence of climate change, the globally extensive studies identified here are consistent with projections of increased forest mortality and suggest that some forested ecosystems may already be shifting in response to climate.

Climate change and cattle nutritional stress. Craine JM, et al. (2010). *Global Change Biology*, 16(10):2901-2911. http://dx.doi.org/10.1111/j.1365-2486.2009.02060.x

Changes in climate can potentially alter grazed ecosystems dramatically, yet the effects of changes in temperature and precipitation on forage (cereal crops) quality and quantity are not well understood. These changes will, in turn, affect the nutrition of grazing animals such as cattle. In this study, the authors investigated how temperature and precipitation can affect forage protein and energy availability in the nutrition of cattle. Over 21,000 measurements of cattle fecal chemistry were acquired over 14 years in the continental U.S. Two indices of the amount of protein and energy available to grazers (crude protein and digestible organic matter, respectively) were analyzed with respect to measures of temperature and precipitation, and variations within and among eco-regions determined.

Results showed that increased temperatures and declining precipitation decreased dietary crude protein and digestible organic matter for most regions. This suggests that cattle are likely to become more protein-limited if climates become warmer and drier in these areas. Within regions, quality declined with increased temperatures, while the effects of precipitation varied. Forage quality patterns for California and the southwest did not relate to climate in the same way as the rest of the U.S. The authors hypothesize that California and the southwest may be characterized by specific environmental features, animal management practices, or forage management practices that cause deviations from the overall trend.

The researchers state that the data suggest that cattle will experience greater nutritional stress in the future from climate change, requiring changes in forage management or livestock management practices. In addition, future declines in forage quality could lead to greater methane production from cattle, as methane production increases per unit of gross energy consumed as diet quality declines.

Modeling plant ranges over 75 years of climate change in California, USA: Temporal transferability and species traits. Dobrowski S, et al. (2011). *Ecological Society of America, Ecological Monographs*, 81(2):241-257. http://dx.doi.org/10.1890/10-1325.1

Species distribution models (SDMs) are widely used to examine potential range shifts and extinction risks under climate change scenarios. SDM projections are based on a

critical assumption that the models are transferable through time—an assumption which is largely untested. *Transferability* addresses the ability of a distribution model calibrated in one context (e.g., historical habitat conditions) to make useful predictions in a different context (e.g., future habitat conditions). This study aims to address two questions that will help advance current understanding of the predictive ability of SDMs: 1) Are SDM projections transferable in time? and 2) Does temporal transferability (i.e., generalizability or applicability of inferences obtained in a study to other time periods) relate to species ecological traits?

To address these questions the authors developed SDMs for 133 vascular plant species using data from the mountain ranges of California from two time periods: the 1930s and the present-day. Climate data corresponding to the two time periods were used in the evaluation. The investigators generated both forecasts and hindcasts of plant species distributions, as follows: models calibrated with historical data were used to generate projections over 75 years of measured climate change, which were compared against current distributions. Similarly, they used contemporary data to calibrate models, and generated hindcasts which were compared to historical data. These results were analyzed to quantify transferability, and to relate transferability to species ecological traits, including whether it is endemic to the area, dispersal distance (distance a species can move from an existing population or the parent organism), prevalence and fire adaptation.

The study showed that variability in model performance was driven predominantly by species traits rather than model algorithm or time period of model calibration. Non-endemic species with greater dispersal capacity, intermediate levels of prevalence, and little fire adaptation had higher transferability than endemic species with limited dispersal capacity that rely on fire for reproduction. Further, the species traits associated with predictability in a single time period may not be related to transferability between time periods. The authors note that despite the many limitations of using SDMs for forecasting climate change responses, they remain the most plausible means by which climate change scenarios can be translated to ecological outcomes. However, the authors' findings stress the need for greater attention to the assessment of SDM transferability in climate change impact studies.

Drivers of change in estuarine-coastal ecosystems: Discoveries from four decades of study in San Francisco Bay. Cloern JEJ and AD Jassby (2012). *Reviews of Geophysics*, 5050, RG4001. http://dx.doi.org/10.1029/2012RG000397

See summary under *Impacts on biological systems, Impacts on animals, Population abundance and ecological interactions*, page 145.

Rapid vegetation redistribution in Southern California during the early 2000s drought. Fellows AW and Goulden ML (2012). *Journal of Geophysical Research: Biogeosciences*, 117(G3):G03025. http://dx.doi.org/10.1029/2012JG002044

Climate change in semi-arid, mid-latitude mountain environments is expected to shift vegetation upslope due to changing spatial patterns of temperature and water availability. Vegetation growing near its low-elevation range limit may prove especially vulnerable to mortality and decline, underscoring the need to better understand the mechanisms that contribute to the resilience and persistence of these ecosystems. In this study, the authors investigated the altitudinal pattern of conifer mortality that occurred from 2002 to 2004 in Southern California's San Jacinto Mountains. They focused on three questions: (1) How did mortality vary with elevation? (2) How were vegetation distributions impacted? (3) Was the mortality unique in a historical context?

The investigators established a series of vegetation sampling transects in 2007–08 along an elevation gradient on the western slope of the mountains. Transects were 300 meters long and located at 122 meter elevation intervals from 1295 to 3002 meters. The fractional cover of a species or group of species was calculated as the sum of species or group cover divided by the length of the sampling transect. Historical records of annual precipitation, monthly mean temperature, and annual temperature for the California Southern Interior Region were obtained from the California climate tracker website. A database was used to search the Los Angeles Times newspaper for historic reports of tree mortality in Southern California's mountains.

The authors found that conifer mortality was focused in the lower portion of the mid-montane conifer range, which drove the conifer distribution upslope. The tree death observed was well above the long-term mean mortality reported for Californian montane forest. There is scientific consensus that drought was the primary immediate cause of the 2002–04 tree mortality. Southern California's Southern Interior Region received 48 percent of average precipitation in 2002, making it the 8th driest year in the 116 year record. The preceding five year mean precipitation was 84 percent of average in 2002 and 69 percent of average in 2003. Annual temperatures were above average in 2002 and 2003. The rates of mortality observed were consistent with those reported for the early 2000s by other researchers working in Southern California's mountains.

The early 2000s mortality and associated vegetation redistribution were interpreted to be a response to natural decadal to centennial climate variability. The authors hypothesize this natural mode of response will dominate the early response of semi-arid forest to global climate change and complicate efforts to identify and attribute the local impacts of climate change. Attribution of biotic responses to global climate change is difficult at small spatial scales, over short time periods, and for single events. Thus, according to the authors, attribution may prove particularly difficult in the Southwestern United States, where the initial impact of global climate change on vegetation may prove almost identical to the impact of natural climate variability.

Climatic limits on foliar growth during major droughts in the southwestern USA. Weiss J, et al. (2012). *Journal of Geophysical Research,* 117:GO3031. http://dx.doi.org/10.1029/2012JG001993

This study evaluates how vegetation might respond to future droughts, assuming milder winters and hotter summers, across the complex and mountainous terrain of the United States Southwest. As temperatures rise and droughts become more severe, trees are increasingly facing extremely stressful growing conditions, especially in low to middle elevations. When the air is hotter and drier, it becomes more difficult for plants to conserve water while taking up CO_2, and renders them more susceptible to insect pests.

The researchers computed indices that represent climatic limits on foliar growth during the 1950's and 2000's droughts using gridded observational meteorological data. They used a growing season index that considers day length, cold temperature limits and "vapor pressure deficit" (VPD) to map and compare potential plant responses to major regional droughts during the two periods. VPD, a key source of plant stress, is defined as the difference between how much moisture the air can hold when it is saturated and the amount of moisture present in the air. During droughts the atmosphere acts like a sponge sucking up moisture from the ground surface, including from plants. Both drought periods led to widespread tree die-offs, and comparisons of climatic indices between them reveal how both warming and drying affect the degree of mortality in different areas. The researchers mapped relatively extreme values of VPD for areas of tree die-offs during the most recent drought using annual aerial surveys conducted by the U.S. Forest Service.

The study suggests that as regional warming continues, drought-related plant stress associated with higher VPDs will intensify and spread from late spring through summer to earlier and later parts of the growing season, as well as to higher elevations. This could lead to even more severe and widespread plant stress. The results are in line with other trends of warming-related impacts in the Southwest over the past 30 years, including earlier leaf-out and flowering, more extensive insect and disease outbreaks, and an increase in large wildfires. The authors note that the VPD and other climate indices can identify areas sensitive to future disturbances and can help plan how to direct or engineer the outcomes of vegetation change in a warmer world.

Chapter 3: Climate Change and the Relevance of Historical Forest Conditions, Safford HD, et al. (2012). In*: Managing Sierra Nevada Forests,* General Technical Report PSW-GTR-237. North M (Ed.). Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. http://www.fs.fed.us/psw/publications/documents/psw_gtr237/psw_gtr237_023.pdf

Climate change, land use change, pollution, and other anthropogenic stressors have reduced the extent of habitat for native plants and wildlife. Restoration and ecosystem management practices rely on the characterization of "properly functioning" reference

states, or sites whose ecological conditions have been undisturbed by human activities. Such sites are difficult to find and frequently must be defined from historical range of conditions. Many scientists question the application of historical reference conditions despite rapid and profound changes in climate and land use.

In this chapter, part of a larger United States Department of Agriculture (USDA) report, the authors review the nature of climate change in the Sierra Nevada, focusing on recent, current, and likely future patterns in climates and climate-driven ecological processes. The authors then discuss the value of historical reference conditions to restoration and ecosystem management in a rapidly changing world. The climate trend portion of this chapter is drawn from a series of climate change trend summaries that were conducted for the California national forests by the U.S. Forest Service, Pacific Southwest Region Ecology Program in 2010 and 2011.

Observations of climate change effects include rising minimum temperatures, reduction in snowpack and earlier melting, changing stream hydrology, increased frequency of large wildfires, increases in tree mortality in lower and mid-elevation forests, and change in tree densities and species' geographic ranges. Over the next century, average temperature in the Sierra Nevada is predicted to rise 2-4ºF in the winter and 4-8ºF in the summer. Models suggest snowpack will decrease significantly and the annual summer drought may intensify, but changes in precipitation may differ between northern and southern California. Changing disturbance regimes are likely to be the primary influence on vegetation types and distributions.

The authors conclude that historical ecology can provide insight to management focused on ecological processes rather than forest structure. Effective management practices may involve removing or reducing non-climate stressors, including restoring heterogeneity of forest conditions.

Climatic correlates of tree mortality in water- and energy-limited forests. Das AJ, et al. (2013). *PLOS One*, 8(7):e69917.
http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0069917

Recent increases in tree mortality rates across the western United States are correlated with increasing temperatures, but mechanisms remain unresolved. Increasing mortality could predominantly be a consequence of temperature-induced increases in either (1) drought stress resulting from increasing climatic water deficit (an index of evaporative demand that is not met by water), or (2) the reproduction, survivorship and effectiveness of tree-killing insects and pathogens. The authors hypothesize that the first mechanism dominates in water-limited forests where growth and other biological processes respond most strongly to changes in water availability, such as in mountain ranges at lower elevations. The second mechanism might be expected to become more important in energy-limited forests where biological processes respond most strongly to temperature changes, such as in higher mountainous elevations.

Using mortality data from 1982–1996 for forest plots in coniferous stands within California's Sierra Nevada mountain range, the authors investigated the two possible mechanisms behind increasing tree mortality. Each plot was counted annually for tree mortality and at 5 year intervals tree diameters were re-measured and new recruitment recorded. Historical values of monthly-averaged precipitation and air temperature in a gridded map format was obtained from the empirically-based Parameter-Elevation Regressions on Independent Slopes Model (PRISM). Statistical models were developed relating changes in tree mortality to changes in temperature and climatic water deficit. Changes in tree mortality rates in the forests of the Sierra Nevada were forecast through the year 2100.

The authors found that in water-limited (low-elevation) forests, mortality was decidedly best modeled by climatic water deficit, consistent with the first mechanism. In energy-limited (high-elevation) forests, deficit models provided only marginally better fits, suggesting that the second mechanism is increasingly important in these forests. The authors could not distinguish between models predicting mortality using absolute versus relative changes in water deficit, and these two model types led to different forecasts of mortality vulnerability under future climate scenarios. The authors note that the results provide evidence for differing climatic controls of tree mortality in water- and energy-limited forests, while highlighting the need for an improved understanding of tree mortality processes.

Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. Richardson AD, et al. (2013). *Agricultural and Forest Meteorology* 169:156-173. http://dx.doi.org/10.1016/j.agrformet.2012.09.012

Recent years has shown a surge of interest in the field of phenology. Scientists now recognize the relevance of phenology to global climate change. For example, documented shifts in phenology serve as robust indicators of the impacts of climate change and variability on natural and managed ecosystems. Furthermore, climate change impacts on both community structure and ecosystem function will be partially controlled by the response of the phenology of individual organisms to a changing change.

The main objective of this review is to highlight the diverse ways in which phenology mediates feedbacks of terrestrial vegetation to the global climate system. It begins with a review of climate change impacts on phenology in different ecosystem types, paying special attention to phenological shifts that are expected, or projected, to occur in the future. It explores those climate system feedbacks in which phenology plays a key role, and examines how these feedbacks might be affected by future phonological shifts. Finally, it provides an overview of different approaches to modeling phenology and suggests ways in which the uncertainties in forecasts of phenological shifts might be reduced. The paper is organized into three sections:

Impacts of climate change on phenology

A review of the recent literature on climate change impacts on phenology, concentrating on important transitions (e.g., leaf phenology); identification of the key environmental drivers (e.g., temperature, precipitation) for phenology in major biomes; and it highlights knowledge gaps with respect to forecasting future shifts in phenology.

Feedbacks of vegetation to climate that are mediated by phenology
A discussion which focuses on the following mechanisms through which vegetation influences the climate system and the role of phenology in these feedbacks: albedo, surface roughness length, canopy conductance, water and energy fluxes, photosynthesis and CO_2 fluxes. Where possible, the authors attempt to quantify the degree to which shifts in phenology may influence the strength of these feedbacks.

Modeling and forecasting phenology
An overview of phenological modeling and suggestions how future modeling efforts might be improved. Models to predict phenological transition dates are needed for many different applications, including: (1) inferring the physiological mechanisms or environmental thresholds and drivers that control phenology; (2) forecasting of climate change on phenology; and (3) representing the seasonal trajectory of vegetation development and senescence and associated physiological activity in large-scale models.

Hierarchical responses of plant–soil interactions to climate change: consequences for the global carbon cycle. Bardgett RDet al. (2013). *Journal of Ecology*, 101(2):334-343. http://dx.doi.org/10.1111/1365-2745.12043

Climate change impacts biogeochemical cycles via a variety of mechanisms that involve interactions between plant and below-ground communities. Of these cycles, one that has attracted recent attention is the terrestrial carbon cycle, due largely to concerns about the potential for climate change to destabilize ecosystem carbon fluxes and thus amplify climate change. There is evidence that climate-induced changes in the growth and structure of plant communities will alter the amount and quality of plant-derived carbon entering soil via root exudates and dead plant material, and that this in turn can affect soil organisms and the processes of carbon cycling that they drive.

This paper presents a framework that identifies a hierarchy of mechanisms by which changes in climate indirectly impact on ecosystem carbon dynamics at three levels of response: individual, community reordering and species immigration and loss.

- **Individual responses.** Individual responses involve changes in the activity, metabolism, behavior and phenology of organisms, without altering community structure, at least in the short term. At this level, plant and soil communities are coupled to environmental cues like temperature and moisture, which are driven by short-term changes in weather and climate.

- **Community reordering.** The short-term physiological and phonological changes to individual organisms caused by changing precipitation patterns, temperature increases, and elevated CO_2 can lead to community reordering over years or decades (both above-ground and below-ground). Community reordering involves changes to species abundance, but not to the extinction or invasion of species. Changes in plant community structure alter the amount and quality of organic carbon entering the soil and modify the chemical and physical properties of the soil.

- **Species immigration and loss.** The long-term consequence of individual responses and community reordering in response to climate change is the entry and loss of species from ecosystems, both above- and below-ground. The consequence of these changes is that entirely new functional attributes may be added to the ecosystem or lost; new biotic interactions between species, both above-ground and below-ground, can emerge, while existing biotic interactions may cease.

The hierarchical framework is used to illustrate how climate change can affect plant-soil interactions across different scales, from quick individual responses at local levels to longer term impacts caused by community reordering and species immigration and loss.

The sensitivity of forest water use to the timing of precipitation and snow melt recharge in the California Sierra: implications for a warming climate. Tague C and Peng H (2013). *Journal of Geophysical Research: Biogeosciences*, 118(2):875-887. http://dx.doi.org/10.1002/jgrg.20073

Terrestrial vegetation and biogeochemical processes are highly sensitive to the timing and amount of water availability. Within the western United States, water availability is an important control on ecosystem productivity and vulnerability to disturbances such as fire, insects and drought-related mortality. Many western forests are located in snow-dominated mountain watersheds that are expected to show strong sensitivity to climate warming. Earlier snowmelt and reduced snow accumulation due to warming temperatures have been linked with earlier snowmelt runoff and increased peaks and reductions in summer streamflow. This study uses a hydro-ecological model to assess whether the extent of snowpack and the timing of snowmelt are significant controls on water availability in forests of Central California Sierra.

The authors used forty years (1960 – 2000) of historic climate data from the Central California Sierra to model interannual and spatial variation in forest evapotranspiration. Evapotranspiration was considered a surrogate for forest water use because over 80 percent of forest evapotranspiration is typically due to the transfer of water through vegetation. To investigate the potential impact of a warming climate, the authors applied a 3º C increase across the historic daily temperature dataset and repeated the analysis. The hydro-ecological model used in this study was previously validated in similar settings.

Changes in evapotranspiration were primarily linked to total precipitation. However, the extent of accumulated snowpack, and timing of water inputs (precipitation and snowmelt), acted as a distinct secondary control on evapotranspiration. With more snowfall, water recharge occurs later in the year, when forest water demand is higher. If more precipitation falls as rain, then early timing of soil water recharge can lead to greater summer moisture stress.

Changes in evapotranspiration specific to the 3º C warming scenario were linked to several variables. For example, annual evapotranspiration increased in some years due to warmer temperatures but decreased by as much as 40 percent in other years due to an earlier timing of snowmelt. The warming simulation substantially altered snow accumulation and decreased peak flows from snowmelt. The average day of complete snowmelt occurred one month earlier, which could decrease water availability in summer. Large declines in water availability and use, even in isolated years, may have important implications for drought stress vulnerability. These results highlight scenarios that may lead to increased drought stress under a warming climate in snow-dominated mountain regions. The authors plan to further refine this analysis by incorporating additional ecosystem dynamics into the model.

Resilience to climate change in coastal marine ecosystems. Bernhardt JR and Leslie HM (2013). *Annual Review of Marine Science*, 5:371-392. http://dx.doi.org/10.1146/annurev-marine-121211-172411

See summary under *Impacts on biological systems, Impacts on animals, Population abundance and ecological interactions*, page 147.

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 include 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.

Driving forces of global wildfires over the past millennium and the forthcoming century. Pechony O and Shindell DT (2010). *Proceedings of the National Academy of Sciences*, 107(45):19167-19170. http://dx.doi.org/10.1073/pnas.1003669107

Recent bursts in the incidence of large wildfires worldwide have raised concerns about the influence climate change and humans might have on future fire activity. It is still unsettled whether climate or direct anthropogenic influence (fire ignition and suppression) are more important in determining global fire trends. In this study, the authors use fire and climate modeling, combined with land cover and population estimates, to gain a better understanding of the forces driving global fire trends.

The authors developed a "fire representation method" for global climate models in an attempt to reproduce past millennium fire activity trends and separate climatic and anthropogenic effects. The method estimates fire activity based on vegetation density, ambient meteorological conditions (temperature, relative humidity, and precipitation), availability of ignition sources (lightning and anthropogenic), and fire suppression rates. Historical estimates on simulations of climate conditions are based on the Goddard Institute for Space Studies general circulation model and land-use and population density reconstructions from the History Database of the Global Environment. The simulated climate variations and land-use changes are used to estimate baseline fire activity trends and population densities are used to assess direct anthropogenic effects (fire ignition and suppression, both increasing with population density), assuming fire suppression effectiveness to increase with time.

The model successfully reproduced global fire activity record over the last millennium and reveals distinct regimes in global fire behavior. Until the late 18th century, simulations either with or without direct anthropogenic influence agree well with reconstructed data, suggesting that during this period global fire activity was primarily climate-driven, whereas human influence remained relatively small. Following the Industrial Revolution, model results suggest a stronger influence from direct anthropogenic activities (e.g., fossil fuel burning, population expansion), which in the 19th century became the dominant driver of global fire activity trends. Around 1900 there is a sharp downturn in global fire activity, despite increasing temperatures and decreasing precipitation. This downturn resulted from increasing fire suppression and decreased vegetation accompanying population growth. Future projections indicate rapidly rising temperatures and regional drying will create an unprecedented fire-prone environment, notably in the western United States.

According to the authors, results from this study suggest a possibility that in the future climate will play a considerably stronger role in driving global fire trends, outweighing direct human influence on fire (both ignition and suppression), a reversal from the situation during the last two centuries.

Trends in wildfire severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau and Southern Cascades, California, USA. Miller J and Safford H (2012). *Fire Ecology*, 8(3):41-57. http://www.calforests.org/wp-content/uploads/2013/06/130113_Safford_etal_trends_in_fire_severity.pdf

Studies have shown that wildfires over the last four decades have become larger, and large fires have become more frequent across the western U.S. An analysis of a 1984 to 2006 dataset of satellite images from the Sierra Nevada Forest Plan Amendment (SNFPA) area of eastern California and western Nevada concluded that the proportion of fire area burning at high severity has risen over time. However, no statistical assessment was made of the temporal trend in high-severity fire area because the dataset was incomplete in the early years of the study period. This study used a more comprehensive database of fire severity from 1984 to 2010 for the SNFPA area in order to show the temporal trend in area of high severity fire for several forest types.

The study area included lands within three ecological sections: the Sierra Nevada, the Modoc Plateau and the southern Cascades. The target forest types-- yellowpine, mixed conifer and red fir-- comprise over 50 percent of the forestlands in the study area. The database included all wildfires greater than 80 hectares in size between 1984 and 2010 that occurred at least partially on the SNFPA national forests. The high-severity category represents stand-replacing fire (i.e., the forest was reset to an earlier, non-forested seral condition). The authors conducted a statistical assessment of temporal trend in area of high-severity fire by grouping the forests as yellow pine-mixed conifer (YPMC) and red fir (RF). Differences in percentage of high severity between small and large fires were also tested to determine if fire effects were related to conditions that led to fires getting large.

The analysis showed that the percentage of total high severity per year for a combination of yellow pine or Jeffrey pine and mixed conifer forests increased significantly over the 27-year period. The annual area of high-severity fire also increased significantly in YPMC forests. There was no trend in percentage of high severity for fires of any size in RF forests. The results suggest that the positive trend in percentage of high severity in YPMC is due to two factors: 1) an increase in the percentage of high severity in large fires, and 2) the absence of years without any large fires after 1993. Overall, the results confirm that forests of eastern California and western Nevada form part of the southwestern U.S. pattern over the last two to three decades showing statistical increases in the area of high-severity component of large fires. The authors state that these trends have important implications when strategizing how to manage SNFPA forests given the predictions of more large fires due to climate change.

APPENDIX
Search Methodology

Publications were identified and selected for inclusion in this bibliography using the following approach.

1. An initial literature search was conducted using the following search query for publications released during the years 2010 to 2013:

   "climate change" AND "California"
   "climate change" AND "California" AND "impacts"

   Databases searched were Google Scholar, SCOPUS and Web of Science.

2. A separate Google Scholar search was conducted using the names of researchers who had contributed to OEHHA's climate change indicator reports. This is intended to allowed OEHHA to track recent monitoring data and new research for purposes of updating or developing indicators for future reports.

3. An additional literature search was conducted for papers on topics of currently receiving much attention from the scientific community, governmental agencies, and the popular press. Examples include: acidification, wildfires, extreme weather events, drought, and winter chill.

4. In addition to the literature searches, staff routinely monitored certain environmental newsletters, and websites of research institutions and government entities for articles and reports that may be of interest. A number of references were identified through this mechanism.

5. 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.

   New scientific understanding, observational data or current or past conditions, not future projections or policy measures. References must 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.

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 on controlled experimental studies were also excluded.

6. Search results were organized into the following groups. Except for authoritative reports, the four groups are those used to categorize indicators in OEHHA's 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*