Ecological Consequences of Climate Change

Mechanisms, Conservation, and Management

Edited by

Erik A. Beever and Jerrold L. Belant

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Preface

Although the ultimate impetus for the book arguably had its nascence decades earlier in the Industrial Revolution, the idea for this book came in a practical sense during the lead-up to a symposium on biological responses to contemporary climate change at the 2007 international conference of The Wildlife Society in Tucson, Arizona. Dr. Erik Beever has been researching the changing distribution of an alpine mammal (*Ochotona princeps*, the American pika) in the Great Basin of western North America since 1994, and although climate was among the original suite of hypothesized determinants of the species' distribution since the beginning of the research, continuing investigation has suggested that climatic influences have played a stronger role in shaping the pattern of local extinctions in the years after 1999 compared to during the latter half of the twentieth century. In that research, as in much of the early research on biological response to contemporary climate change, the key challenge has been trying to divine the "why" and the "how" behind the "what" and "when"—that is, the *mechanisms* behind any changes in ecological systems in response to contemporary climate change.

We have consequently asked all authors to focus part of the discussion in each of their chapters on mechanisms, for two reasons. Understanding the hows and whys of these responses not only provides a more complete understanding of the dynamics associated with ecological responses, but also it is exactly that understanding that is needed to best inform strategies of mitigation, adaptation, conservation, and management of affected ecosystems and their components. Mechanisms are just beginning to be addressed rigorously, for good reason—they require much more in-depth understanding of the relevant natural history of species and ecosystem components involved, more critical thinking before beginning the fieldwork, and often more time and money than if mechanisms were ignored (i.e., simply documenting any changes). It quickly becomes apparent that much still remains to be learned, and humility in the face of so many unknowns and sources of uncertainty seems prudent. We feel that it is this focus on mechanisms—as well as our melding of empirical research, management, and conservation—that will distinguish this book from its contemporaries and perhaps even from later books on the topic.

Both editors have spent their careers working around the nexus of research and management of ecological systems, and this book clearly reflects that applied approach. We have asked authors to not only provide case studies to exemplify their messages throughout their chapter, but also to provide the "so what?" implications of their chapter for management and conservation of the systems they discuss. We feel honored and fortunate to have been able to work with such an experienced, widely respected, and capable group of authors, who fortuitously also happen to be wonderful individuals with whom to work. They hail from six different nations around the world and work not only on diverse spatial and temporal scales, but also on a vastly divergent collection of ecosystem components. Our vision was that this heterogeneity would best exemplify the diversity of biological responses that may be expected in the coming decades (and have already begun to be observed).

Mirroring the progression of research surrounding ecological responses to contemporary climate changes, we have sought to first describe how climate is changing, then describe the basic responses of wildlife and other ecosystem components to climatic variability and change, then discuss the management strategies in response to such climatic influence, then consider implications for various scales of conservation, and then finish with a vision to the future that springs from what we know already to explore gaps in our understanding and research frontiers. We suspect that although the novelty of investigating biotic response to climate change may wane with time, climate will remain a pervasive and profound driver of ecosystem dynamics for decades to come, and likely with increasing strength. Thus, our hope is that this book initiates discussions, foments critical reviews of the ideas contained within, and informs future research, management, and conservation during this period of the worldwide natural experiment in which we currently find ourselves engaged.

Acknowledgments

An undertaking of this magnitude could never have come to fruition without the concerted effort of numerous individuals. Dr. Beever would like to thank some of the prominent biology-oriented and other mentors in his life, including Guy Malain, Sheila Ward, Tom Schoener, Frank Joyce, Peter Brussard, David Pyke, Mary Pat White, and his parents; special thanks are due to his wonderful wife Yuriko for her patience and support. Dr. Belant similarly thanks Layne Adams, Richard Dolbeer, Erich Follmann, and Bruce Leopold for their professional guidance, and Mary-Kay Belant for her support and encouragement throughout this process.

The patient staff at Taylor & Francis—Pat Roberson, Jill Jurgensen, Robin Lloyd-Starkes, and especially Randy Brehm—helped shepherd the organizational process along. Chapter authors deserve special thanks for their willingness to endure multiple rounds of editing necessary to achieve a polished final form.

Thanks are also due to the Biological Diversity Working Group of the Wildlife Society, from which a symposium sprung that fostered the germination of this book. Finally, we commend researchers seeking to "push the envelope" (not the bioclimatic type) to develop theory, algorithms, and empirical research needed to observe, understand, and interpret the multitude of biological responses to contemporary climate changes, as well as wildlife and conservation practitioners in land-managing agencies, non-governmental organizations (NGOs), and other organizations working "in the trenches" to balance livelihoods with leaving a rich biotic heritage for future generations to enjoy and take sustenance and inspiration from, and to watch climate interact with other ecosystem drivers to shape the composition and function of biological systems.

About the Editors

Dr. Erik A. Beever received his BS in biological sciences from the University of California, Davis in 1993 and his PhD in ecology, evolution, and conservation biology from the University of Nevada, Reno, in December 1999. He has published over 50 articles in diverse scientific journals and in numerous subdisciplines of biology. He has performed field research on plants, soils, amphibians, birds, reptiles, fishes, and insects, as well as small, medium, and large mammals. His work has spanned salt-scrub, sagebrush-steppe, alpine, subalpine, subarctic, riparian, primary and secondary temperate and tropical forests, and coastal ecosystems of the western hemisphere. In addition to seeking to understand mechanisms of biotic responses to climate change, he has also focused on disturbance ecology and monitoring in conservation reserves, all at community to landscape scales, as well as other topics of conservation ecology, wildlife biology, and landscape ecology. He is a member of the IUCN Protected Areas Specialist Group, the IUCN Lagomorph Specialist Group, as well as the Wildlife Society, the Society for Conservation Biology, the American Society of Mammalogists, Sigma Xi, and the Union of Concerned Scientists.

Dr. Jerrold L. Belant is an associate professor of wildlife ecology and management, and director of the Carnivore Ecology Laboratory at Mississippi State University. He received his PhD from the University of Alaska, Fairbanks. Dr. Belant has authored over 100 publications in wildlife ecology, conservation, and management. He is the chair of the IUCN Species Survival Commission's Small Carnivore Specialist Group and a member of the International Federation of Mammalogists. Dr. Belant is also editor of *Small Carnivore Conservation* and associate editor for *Ursus*, *Natural Areas Journal*, and *Latin American Journal of Conservation*.

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Top Left. Consolidated pancake ice off the coast of Greenland. Decreases in the extent of polar sea ice have been one of the most pronounced inter-annual trends in the world, among abiotic indicators of recent climate change. Photo courtesy of Andy Mahoney, National Snow and Ice Data Center.

Top Right. Newborn Olive Ridley turtle (*Lepidochelys olivacea*), on a beach in Junquillal, on the Pacific coast of Costa Rica. Because the sex of marine turtles is determined by the incubation temperature of eggs in the sand, forecasts of increasing temperatures have spawned concern that over-abundance of females and scarcity of males may compromise population recovery. In addition, rising sea levels may erode nesting beaches in which infrastructure prevents their gradual shift landward. Photo copyright of World Wildlife Fund International/Carlos Drews.

Middle Left. Blue-spotted salamander (*Ambystoma laterale*), on Rocky Island, Apostle Islands National Lakeshore, Wisconsin, USA. Altered climatic conditions, UV radiation, and indirect effects of climate (e.g., altered suitability for pathogens and invasive species) have been suggested as contributors to recent declines in numerous amphibian species globally. Photo courtesy of Eric Ellis.

Center. Upper-elevation ecosystems of the Andes in Argentina, near Aconcagua—the highest point in the western and southern hemispheres. Montane ecosystems store drinking water for most of the world's humans, and have been demonstrated to exhibit greater vulnerability to contemporary climate changes than their lowland-habitat counterparts. Photo by Erik Beever.

Middle Right. An American pika (*Ochotona princeps*) in talus of the East Humboldt Range, northwestern Nevada, USA. This species' distribution has changed dramatically within the Great Basin since the early 20th century, apparently in association with changes in climate. Photo by Shana Weber.

Bottom Left. Shrubs, trees, and native and invasive herbaceous plants in Mojave National Preserve, southeastern California, USA. Changes in aspects of climate have been associated with the phenology of plant flowering and with dynamics of plant-species invasions. Photo by Benjamin Chemel.

Bottom Right. Hundreds of blue wildebeests (*Connochaetes taurinus*) and plains zebras (*Equus burchellii*) along their migration route through Serengeti National Park, Tanzania, Africa. This multi-species migration, the largest migration of large mammals in the world, exemplifies concerns about landscape connectivity, as community associations re-assemble and ecological niches shift spatially, under changing climate. Photo by Erik Beever.

Section I

The Basis of Recent Climate Change: Climate-Science Foundations

1 Western Climate Change

Philip W. Mote and Kelly T. Redmond

CONTENTS

INTRODUCTION

Earth's global climate is determined by a balance between absorbed solar radiation and emitted infrared radiation. The amount of absorbed solar radiation in turn is determined by the sun's emissions and the Earth's reflectivity, primarily the fraction of the planet covered by clouds and ice. Infrared emissions come predominantly from gases in the atmosphere: water vapor, carbon dioxide, methane, nitrous oxide, and many more. The atmosphere also emits energy toward Earth, keeping it warmer than it would otherwise be, and providing roughly twice the energy as is provided by absorbed solar energy (e.g., Trenberth et al. 2009). At the surface, the absorbed solar energy plus atmospheric infrared energy is balanced globally by radiation of infrared radiation plus latent and sensible heat flux (Trenberth et al. 2009), all of which are mediated by vegetation, especially moisture fluxes. In turn, the expression of global climate and of atmospheric fluctuations helps determine the distribution, health, function, reproductive rates, and much more, of organisms on the landscape.

Through technology and sheer numbers, humans have acquired the ability to modify climate in many ways. Chief among these are the production of (1) greenhouse gases, such as carbon dioxide, ozone, nitrous oxide, methane, chlorofluorocarbons; and (2) aerosols that originate from disturbed soils, soot, ash, pollution, and gases transformed through photochemistry to particles. All of these affect the flow of radiant energy through air. Deforestation, irrigation, agricultural practices, paving, and other kinds of development change land surface properties and influence the dynamics of energy exchange, heat transfer, and surface winds. Recent findings indicate that changes in atmospheric particle concentration can greatly alter cloud properties and reduce precipitation efficiency and amount (e.g., Forster et al. 2007). Anticipated changes in temperature may also affect precipitation type (rain or snow). Changes in atmospheric CO_2, ozone, and other gaseous and aerosol constituents have direct but differential physiological effects on vegetation, species competitiveness, and amount and quality of light, which in turn affect soil moisture and recharge budgets, plant species composition, and community properties.

Assessing historical and future biological responses to global climate change requires an understanding of two causal connections. The first is the connection between the local climate variables and the biological system of interest. Because so many factors are at work simultaneously, this determination is seldom straightforward. For instance, temperature may affect tree growth; however, other climatic and nonclimatic factors like competition for light or other resources might be as important. Put differently, if we knew perfectly how climate would change in the immediate vicinity of an ecological community, how well could we predict the ecological response? The second is the connection between the biologically important local climate variables and global climate drivers like greenhouse gases. In the field of climate research, this connection is called "detection and attribution." These involve whether a change has actually been observed, within measurement error (detection), and whether any such change (e.g., in global average temperature) could have occurred naturally or can confidently be attributed to human activity (attribution; Stott et al. 2000; Broccoli et al. 2003; Meehl et al. 2004). Attribution is most successful when the signal-to-noise ratio is high, that is, when the response of the variable in question to greenhouse-gas forcing is large relative to natural variability. Keeping the signal-to-noise ratio large typically requires considerable spatial averaging and a long period of record (>50 yr) for analysis. The two causal connections are in tension, owing to the inherently conflicting spatial and temporal scales. Detection and attribution are clearest at the global scale over multiple decades, but responses of ecosystems or species to climate are often clearest at the local scale and at shorter time periods.

In this chapter we highlight the meteorological and physical background of observed climate variability and change, and recent attribution efforts related to contemporary climate change. We also describe scenarios of future climate for the western United States. Climate is a principal driver of the natural and managed environmental systems of the western United States, and is such a pervasive influence that its properties and behavior in space and time must be taken into account and factored into the management of western lands and resources (Redmond 2007).

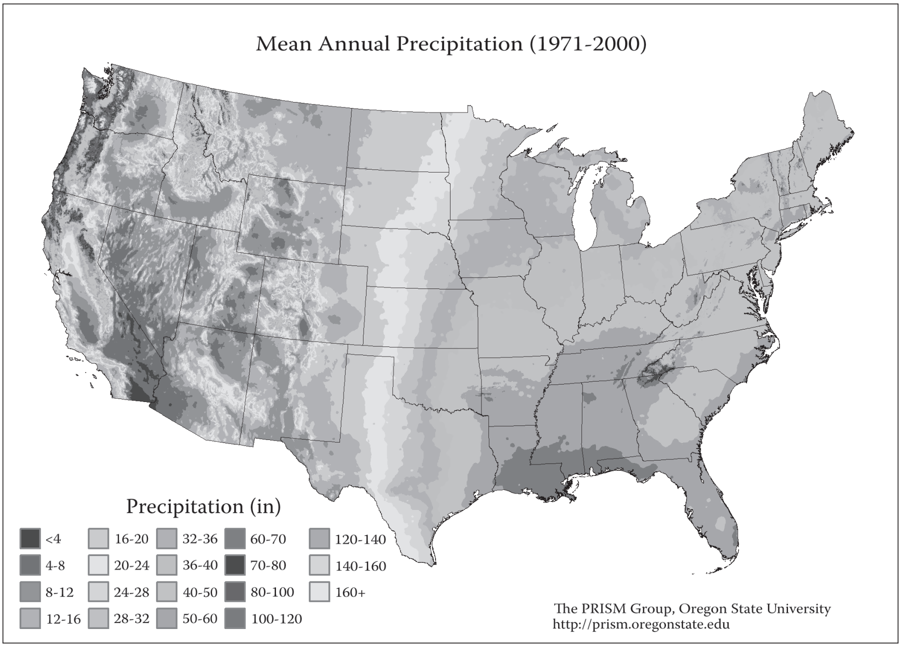

FIGURE 1.1 (See color insert.) Mean annual precipitation from PRISM (Daly et al. 2002, 2004, 2008) for the 1971–2000 period of record. Note the sharp gradients in much of the West.

OBSERVED CLIMATE VARIABILITY AND CHANGE IN THE WESTERN UNITED STATES

The western United States is a land of juxtapositions and sharp contrasts in physiography, climate, vegetation, and other biophysical attributes. In addition to the sharp contrasts across short distances, the West has striking seasonality in precipitation; in most of the West, summer precipitation is substantially less than winter precipitation. Fundamental attributes of average climate, notably precipitation, can change greatly over short distances (Figure 1.1), as can precipitation seasonality, annual amount, and phase (i.e., rain vs. snow). Properties of temporal variability can also vary over short distances (Redmond 2003). Elevation plays a key role in shaping the patterns of temperature and precipitation (Daly et al. 2008), and mountain ranges greatly modify and sometimes cause their own weather. Mountain time series of climatic variables can be very different from those in the adjoining valleys. Large-scale "teleconnections" with other parts of the globe lead to spatially different responses in reaction to faraway phenomena such as tropical El Niño and La Niña events. Examples of observed variability and change, and global processes affecting climate in the western United States are described in the next section.

The fundamental issue is the following: to fully understand the interrelation between ecosystems and the climate system, we must ideally first understand the properties of spatial and temporal variability (and in addition, combined spatiotemporal variability) of each of these two sets of systems, across their characteristic range of spatial and temporal scales. Ecological systems have evolved to selectively take advantage of regularities in physical environmental drivers (such as climate) across a very large range of scales, and in addition must respond to more stochastic variability in both space and time of these drivers, also across a broad range of scales, from that of a stomate or needle (1 mm) to the globe (10,000 km), a range of scales that encompasses approximately 7–10 orders of magnitude.

Temperature Variability and Change

Studies of variability and change in climate variables utilize several common gridded datasets. Station data are the basis for all of these datasets, which make use of different ways of aggregating or averaging station data over regions. Here we use gridded 0.5° (longitude) × 0.5° (latitude) annual mean temperature data from CRUv2.1 (Brohan et al. 2006), which have been widely used in global-trends analyses. We use a domain from the Pacific Ocean to 107.5° west longitude, and from 30 to 52.5° north latitude, and select the longest period for which all grid points have complete records: the 1920–2008 period of record. Figure 1.2 shows the trends in annual mean temperature from the HadCRU dataset. There are a few patches of negative trends over this time period, but for most of the western United States, the trends have been upward.

In order to better understand the time dimension of these changes, we regionally average the HadCRU data to produce a West-wide annual mean temperature each year. Only HadCRU grid points with at least some data in the first 5 and last 5 years are used. We also use the regionally averaged temperature data from WestMap (www.cefa.dri.edu/Westmap) derived from the PRISM dataset (Daly et al. 2008). These two datasets are derived from different station data and give somewhat different results that depend on how elevation–temperature relationships are treated, resulting in a systematic difference stemming from systematic station-grid elevation differences. The time series for the regionally averaged temperature (Figure 1.3) shows a strong upward trend, reflecting the warming of the West during the time period of analysis. The magnitude and frequency of negative anomalies dwindled during the 1970s and 1980s, as nearly every year since 1985 has been near average or above average in temperature. The record warmest year remains 1934 but the warmest 10- and 20-year periods are recent. The two time series differ the most in the early years and consequently have different trends (0.6°C for HadCRU and 1.0°C for WestMap). Slow variations highlighted by the (smoothed) curves are substantially the same, with a bit of warming between about 1910 and 1930, fairly level temperatures until 1970, and then warming.

Dependence of Trends on Elevation

For the mountainous West, a critical question about long-term change concerns the relative rates of warming at mountaintops, mid-slopes, and valley floors. Do these rates differ, and if so, do they vary among the seasons? Whether these rates should be similar depends ultimately on the physical mechanisms for potential variation in rates across elevations. Unfortunately, long-term climate stations in mountainous regions are fairly rare: for example, the state of Washington has no climate-quality stations above 1300 m that provide full annual measurements before 1945 and

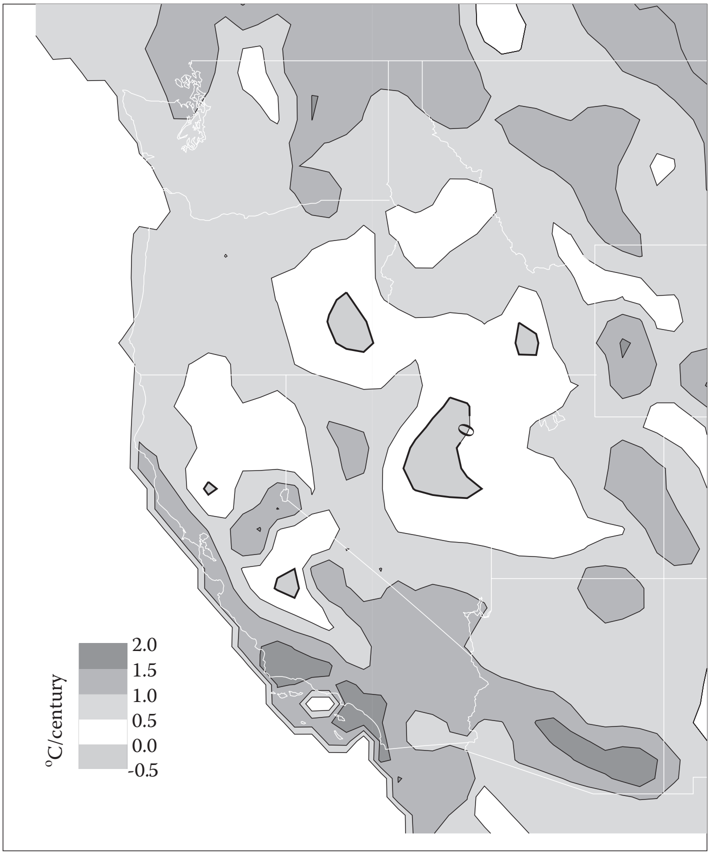

FIGURE 1.2 (See color insert.) Linear trends in temperature (°C/century) from the HadCRU 0.5° × 0.5° dataset, evaluated over the 1901–2000 period. The contour interval is 0.5°C per century.

continue today. In most western states there are at least a few stations above 2000 m, but most are in valley bottoms. In many areas the data are too sparse to draw a conclusion about whether trends in temperature depend on elevation alone.

In evaluating temperature trends in the mountains, for example, the issue of whether temperature trends depend on elevation, a critical question concerns the separate roles of "advection" (the heat carried by the wind) and local surface-energy balance, and different studies have reached different conclusions. Diaz and Bradley (1997) analyzed surface-temperature records at 116 sites and found that many high-elevation sites had warmed more than lower-elevation sites during the twentieth century, but questions have been raised about whether these findings represent true surface trends or are determined by the varying exposure to advection. Changes in free-air temperature (away from the surface, measured by balloon) have generally exceeded surface temperature changes (Karl et al. 2006), but not all studies reach this conclusion (Pepin and Losleben 2002; Vuille and Bradley 2000). Most studies found no clear relationship

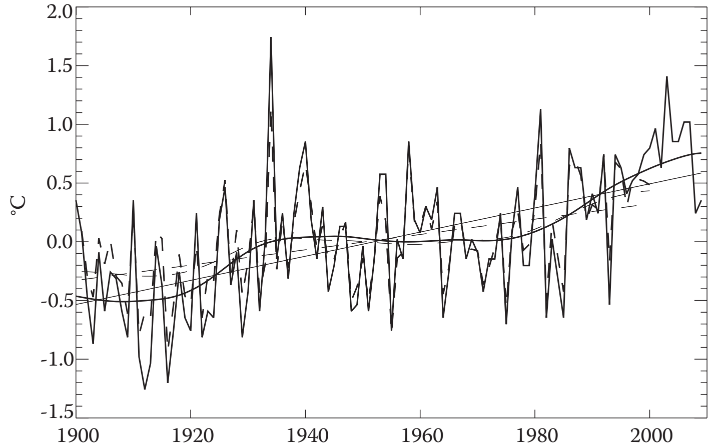

FIGURE 1.3 Values of annual mean temperature over the western United States calculated from the CRUv2.1 dataset (dashed) and the PRISM dataset (solid). Linear trends (straight lines) and slow variations (curves) were calculated using locally weighted regression (loess; Cleveland 1995). For both curves, the mean over the entire record is subtracted.

with elevation (Vuille et al. 2003; Pepin and Seidel 2005; Liu et al. 2006; You et al. 2008). Pepin and Seidel (2005) noted that the correspondence between surface and free-air variability and trends depended on the convexity (hilltop vs. valley or frost hollow) of the terrain in which the station was situated, such that variability at stations higher than surrounding terrain more closely resembled that of the free air, while stations in valley bottoms were more likely to differ from the free air.

As illustrated by Pepin and Seidel, the key question in evaluating the dependence of trends on elevation is the extent to which surface temperatures are determined by local energy balance as opposed to mere exposure to free air. Local advection (drainage winds, upslope winds) can exert significant influence as well. Some areas may remain for some time as cold-air pools and in effect serve as "climate refugia" (Ashcroft 2010; Petit et al. 2003; Bennett and Provan 2008). Another approach to evaluating trends that brought the surface-energy balance into clearer focus was the work of Pepin and Lundquist (2008). Examining trends globally, they noted that the largest warming trends were found at locations whose mean annual temperature was near 0°C, suggesting a strong role for snow-albedo feedback. This observational result was largely corroborated by the regional modeling work of Salathé et al. (2010), who noted the largest warming trends in a future scenario in montane areas presently near snowline. In short, there are ample reasons to believe that topographic complexity may produce considerable small-scale variability in change rates that could rival or exceed (positively or negatively) regionally averaged rates (Daly et al. 2009).

Variability and Changes in Precipitation

Although trends in temperature are positive almost everywhere in the western United States, trends in precipitation are far more diverse. Linear fits are a poor description

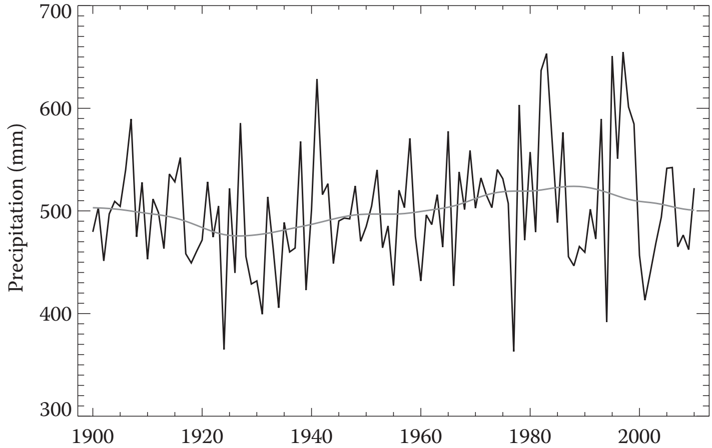

FIGURE 1.4 Water year (October–September) precipitation 1899–1900 through 2009–2010 for the 11 western United States. Data from 4-km resolution PRISM grid using the WRCC Westmap (www.cefa.dri.edu/Westmap/) application. Smooth grey curve calculated using loess as in Figure 1.3.

of the patterns of precipitation variability because the sign of the fit can change over short spatial distances and with slightly different periods of analysis. The time series of total precipitation (which includes the water equivalent in snowfall) for the October through September water year illustrate temporal patterns (Figure 1.4). The time series of average total precipitation for the 11 western states shows some interesting features, especially a pronounced increase in the mid-1970s in both the variance and the year-to-year persistence of precipitation anomalies, as has been noted by Hamlet et al. (2005) and Pagano and Garen (2005). Many of the extreme years—both dry and wet—have occurred since 1975. The increase in year-to-year persistence (i.e., multiyear episodes or regimes) is visible first as several unusually wet years in the early 1980s, which were followed by several unusually dry years in the late 1980s, then several wet years in the late 1990s, then several dry years in the early 2000s. There is little theoretical basis to expect such a shift to accompany rising greenhouse gases, and it may simply be a statistical artifact of a red noise time series.

Hydrologic Responses to Changes in Temperature

Fluctuations in streamflow are closely linked to fluctuations in precipitation, but a large body of literature emphasizes that western hydrology also responds to temperature. An analysis of fine-scale gridded meteorological data, specifically the fraction of annual precipitation falling at temperatures between 0°C and –6°C, what might be called warm snow, illustrates the West's hydrologic sensitivity to temperature fluctuations (Bales et al. 2006). Temperature increases of 2–4°C (likely to occur during the twenty-first century; see the following) during precipitation events could lead to a considerable increase in precipitation falling as rain rather than snow. The more immediate runoff has numerous hydrologic and water-management consequences. The analysis of Bales et al. (2006) shows that within certain elevation bands in the Cascade and Sierra Nevada Ranges, over half of the annual precipitation historically falls in this temperature range. The vulnerability to a change from snow to rain is next greatest in the mountains of Idaho and parts of the Great Basin, and least in the highest and thus coldest parts of Colorado and the southern High Sierra Nevada.

Consistent with the physical sensitivity analysis of Bales et al. (2006), several studies have demonstrated a statistical connection between fluctuations and trends in temperature and fluctuations and trends in various hydrologic variables. Knowles et al. (2006) used weather station data and reported that rain/snow ratios have increased in most of the West since about 1950, with spatial patterns resembling those of temperature change and the temperature sensitivity noted by Bales et al. (2006). Mote et al. (2005) and Hamlet et al. (2005), using observations and modeling, demonstrated that springtime mountain snowpack declined at roughly 75% of locations in the West since the mid-twentieth century. These changes were dependent on elevation (and thus temperature, because temperature usually decreases with elevation), with warmest locations losing the largest fraction of snow. Stewart et al. (2005) showed that streamflow in much of the West has changed in a manner consistent with the observations of declining mountain snowpack. In basins with a significant snowmelt contribution, winter and early spring flows generally increased, summer and late spring flows generally decreased, and the date of peak spring snowmelt shifted earlier by, on average, 2 weeks. Stewart et al. (2005), Hamlet et al. (2005), and Mote (2006) all evaluated the possible contributions of changes in precipitation and of changes in atmospheric circulation over the Pacific Ocean and concluded that the dominant factor in western trends in hydrology was the widespread increase in temperature unrelated to atmospheric circulation.

Increases in temperature with no change in precipitation can cause evapotranspiration (ET) to increase. Hidalgo et al. (2005) estimate an average temperature increase of +3°C could increase potential evapotranspiration (i.e., what evapotranspiration would be if not limited by water availability) by about 6% in California. However, the physiological response of plants to increased CO_2 concentration would likely act to reduce water loss.

Global Teleconnections

Spatial patterns of climate variability in the western United States are correlated with patterns of climate variability in other parts of the world. For example, winter precipitation in the West frequently exhibits a “dipole” pattern (wet in the Pacific Northwest and dry in the Southwest, or vice versa), and that this pattern is strongly related to tropical Pacific Ocean temperatures and to atmospheric pressure patterns in the Southern Hemisphere (Redmond and Koch 1991). The sense of the relationship is such that the phenomenon known as El Niño is associated with wet winters in the Southwest and dry winters in the Northwest and northern Rockies, and that La Niña is associated with dry winters in the Southwest and wet winters in the Northwest and northern Rockies.

There is much popular confusion between the El Niño phenomenon and its effects. El Niño refers to ocean warming in the top 100–200 meters in a narrow band between South America and the international date line, typically within 5° latitude of the equator. The effects of El Niño, by contrast, are global in reach. At time scales between the regular seasonal cycle and several years, El Niño is the single largest contributor to climate variability on earth. The warm area may look small on a map of the Pacific Ocean, but can easily be larger than the United States. The shape, magnitude, extent, duration, and longitudinal position of the warm-water patch can vary from one episode to the next—factors that can significantly influence the impacts of the phenomenon on the West (Hoerling and Kumar 2002). Typical events last 6–18 months and recur irregularly at 2- to 7-year intervals. La Niña refers to unusually cool temperatures in this same area.

El Niño exhibits characteristics of an oscillation in the sense that during one phase of the cycle, forces are at work that lead to the demise of that phase and often even the eventual growth of the opposite phase, like a very complicated pendulum, albeit one subject to irregular forcing by short-term weather events. The atmospheric pressure difference between stations at Tahiti and Darwin (Australia) is negatively correlated with ocean temperatures in the El Niño/La Niña area—a phenomenon known as the Southern Oscillation: it is the atmospheric counterpart of the oceanic El Niño. The magnitude of this correlation, usually strong, has varied somewhat through time (McCabe and Dettinger 1999), so the atmosphere and the ocean each carry somewhat different information. In recognition of the coupled oceanic and atmospheric nature of this vacillation, this phenomenon is called ENSO ("El Niño/Southern Oscillation").

In the Western United States, the effects of El Niño and La Niña are experienced during the cold half of the year, from approximately October through March; summer signals are very weak. The climatic effects of ENSO are also found in streamflow (Andrews et al. 2004; Barnett et al. 2004) where they are greatly accentuated with respect to precipitation (Cayan et al. 1999) in the western states. Because annual tree growth in the Southwest is strongly dependent on prior winter precipitation, these ENSO effects are clearly seen in tree ring widths (Swetnam and Betancourt 1990).

The frequency of El Niño has varied through time. During the period 1947–1976, El Niño occurred relatively infrequently and La Niña was common. A sudden and still unexplained change (the "1976–1977 shift") in the Pacific ushered in an era of much more common El Niño and a virtual dearth of La Niña. This appeared to many observers to have switched again in the late 1990s, although present evidence remains somewhat ambiguous.

In higher latitudes, this slow variation of about 50 years' duration is expressed in a pattern of ocean temperatures, atmospheric pressures, jet stream positions, and ocean currents seen from the tropics to the high latitudes in the Pacific, first described by Mantua et al. (1997) and Mantua and Hare (2002) as the Pacific Decadal Oscillation (PDO) and elaborated by others. They related the PDO to strong differences in salmon abundance between Alaska and the Pacific Northwest. There is much debate about the origin of the PDO, whether it truly is an oscillation, and even whether it really exists except as a response to ENSO (Zhang et al. 1996; Newman et al. 2003) with strong elements of chaotic behavior (Overland et