Chapter 19

Moving Forward with Imperfect Information

COORDINATING LEAD AUTHOR

Kristen Averyt (University of Colorado Boulder)

LEAD AUTHORS

Levi D. Brekke (Bureau of Reclamation), David E. Busch (U.S. Geological Survey)

CONTRIBUTING AUTHORS

Laurna Kaatz (Denver Water), Leigh Welling (National Park Service), Eric H. Hartge (Stanford University)

REVIEW EDITOR

Tom Iseman (Western Governors' Association)

Executive Summary

This chapter summarizes the scope of what is known and not known about climate in the Southwestern United States. There is now more evidence and more agreement among climate scientists about the physical climate and related impacts in the Southwest compared with that represented in the 2009 National Climate Assessment (Karl, Melillo, and Peterson 2009). However, there remain uncertainties about the climate system, the complexities within climate models, the related impacts to the biophysical environment, and the use of climate information in decision making.

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Uncertainty is introduced in each step of the climate planning-and-response process—in the scenarios used to drive the climate models, the information used to construct the models, and the interpretation and use of the models' data for planning and decision making (Figure 19.1).

There are several key challenges, drawn from recommendations of the authors of this report, that contribute to these uncertainties in the Southwest:

- There is a dearth of climate observations at high elevations and on the lands of Native nations.
- There is 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.
- Climate models, downscaling, and resulting projections of the physical climate are imperfect. Representing the influence of the diverse topography of the Southwest on regional climate is a particular challenge.
- The impacts of climate change on key components of the natural ecosystems (including species and terrestrial ecosystems) are ill-defined.
- The adaptive capacity of decision-making entities and legal systems to handle climate impacts is unclear. This creates a challenge for identifying vulnerabilities to climate in the Southwest.
- Regulation, legislation, and political and social responses to climate all play important roles in our ability to adapt to climate impacts and mitigate greenhouse gas (GHG) emissions.
- Climate change is one of multiple stresses affecting the physical, biological, social, and economic systems of the Southwest, with population growth (and its related resource consumption, pollution, and land-use changes) being particularly important.

19.1 Introduction

Climate assessments illustrate how natural resources and managed systems might fare under a variety of climatic and socioeconomic scenarios. Assessments take advantage of the best data and modeling tools and follow scientifically approved methodologies to develop projections of climate impacts to physical, biological, social, and economic systems associated with possible climate futures. Such climate projections are important to the success of adaptive measures (Millner 2012). This assessment of the climate of the Southwest takes a risk-based approach. The intention is to provide the decision-making public with information about the costs and benefits to society associated with different emissions scenarios. Although uncertain, scenarios can help identify risks and appraise our ability as a society to adapt to climate change. Science will never eliminate uncertainty. Even concepts as seemingly simple as gravity are subject to uncertainties in a scientific context. Scientists cannot eliminate uncertainties about climate and related risks. Nonetheless, climate observations and projections can provide useful information. For this reason, characterizing what is known and what is not known about the past, current, and future climate and related impacts is necessary to help decision makers identify appropriate mitigation strategies and adaptive measures.

This chapter summarizes the scope of knowledge and uncertainty about climate in the Southwest. Throughout this assessment, each chapter has outlined key findings about our regional climate. Included with each key finding is a statement of "confidence," i.e., a statement intended to convey the degree of knowledge based on evaluation of available data and scientific interpretations in the literature (Box 19.1). This chapter outlines the uncertainties that collectively present challenges in using climate information to inform decisions. It also highlights cases in the Southwest where climate information—imperfect as it may be—is successfully being incorporated into planning and management. Drawing upon these examples and on the literature pertaining to decision making under uncertainty, this chapter offers steps for moving forward with imperfect information.

19.2 Uncertainty Typologies

The "uncertainty continuum" in Figure 19.1 outlines the process through which the impacts of climate change are projected and indicates numerous points at which uncertainties are introduced. These include everything from the scenarios used to drive models, the information used to construct climate models, and the interpretation and use of the models' data for planning and decision making. Discussed here are three types of uncertainty that can impact climate change: scenario uncertainties, model uncertainties, and communication uncertainties.

Scenario uncertainties

POPULATION, TECHNOLOGY, PRODUCTION, CONSUMPTION AND GREENHOUSE GAS EMISSIONS. Population growth and economic trends are the critical components driving greenhouse gas (GHG) emissions. The scenarios that feed into climate models represent different combinations of assumptions about population change and economic conditions, and show their related trends in greenhouse gas emissions. As described in Chapters 2 and 6, the high-emissions (A2) and low-emissions (B1) scenarios used in this assessment are from the IPCC Special Report on Emissions Scenarios (SRES; Nakićenović and Swart 2000). Emissions scenarios illustrate a suite of possibilities to aid in planning, but they are not perfect. For example, none of the SRES trajectories developed in 2001 presented a scenario that captured the global economic downturn in 2008. The SRES trajectories also did not include the entire suite of social, economic, policy, and regulatory responses that affect adaptive response and ability to mitigate emissions (Hawkins and Sutton 2009). As climate projections move further into the future, particularly beyond the fifty-year mark, accurately capturing population trends, economic trends, and technological advances becomes more difficult. There is no broadly accepted method for quantifying the uncertainties associated with future emissions.

Model uncertainties

ATMOSPHERIC CONCENTRATIONS, RADIATIVE FORCING, TEMPERATURE CHANGE. General circulation models (GCMs, often called global climate models) integrate the components of climate based on observations (Hawkins and Sutton 2009,

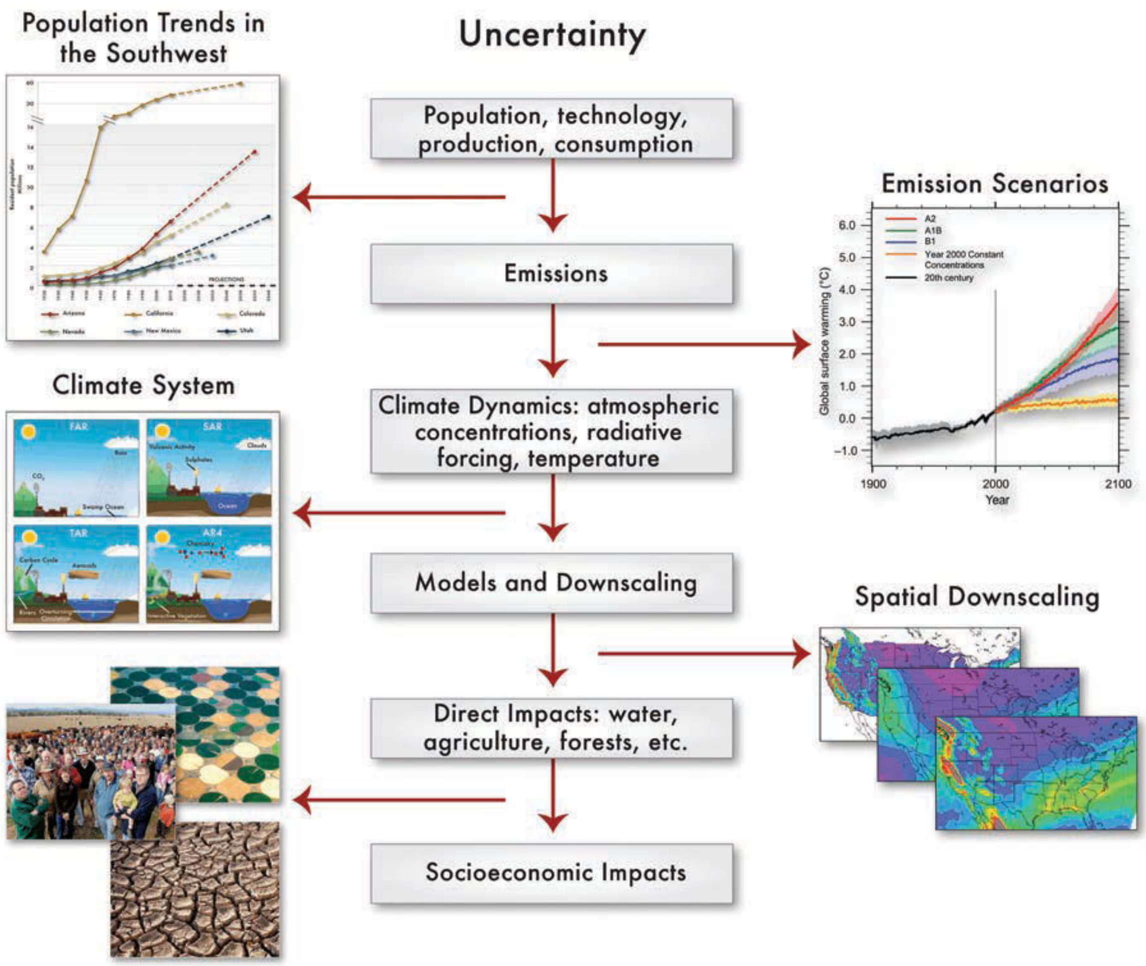

Figure 19.1 Working with uncertainty. Continuum of uncertainties, knowledge gaps and challenges related to projecting future climate changes and their impacts, and assessing vulnerabilities to future changes. See Tables 19.1 and 19.2 for syntheses of knowledge and uncertainties identified by authors of this assessment report. Adapted from Pidgeon and Fischhoff (2011).

2011). Although numerous emissions paths are represented in the GHG scenarios, they do not precisely translate into changes in radiative forcing (i.e., changes in the balance of radiated energy), which can warm or cool the climate system.

Observational data is a key research need that feeds into these uncertainties. Fewer observations make it difficult for scientists to tease out the information they need to accurately represent climate dynamics. In the Southwest, there are minimal climatic and meteorological observations for much of the region, especially at high elevations and on tribal lands—thus impeding our understanding of regional climate processes.

Model uncertainty can also be attributed to factors affecting climate that have yet to be identified (Risbey and O'Kane 2011). Consider the role of aerosols in moderating climate. Prior to 2003, the role of these particulates in the atmosphere and in regulating climate was unknown, and so they were not represented in GCMs. They were an "unknown uncertainty" discovered through scientific inquiry to be important components, even though considerable uncertainty remains about their precise influence on climate processes (IPCC 2007). This raises an important concept: discovering new parts of a climate system may add to the body of climate knowledge while introducing additional uncertainties (Trenberth 2010; Pidgeon and Fischhoff 2011).

GCMs have been shown to exhibit biases when trying to simulate historical climate. These biases vary locally, from wet to dry or warm to cool, and vary seasonally. Assessments adjust for these biases, but the approaches used to identify and correct them can vary. Bias correction can even affect projected climate trends and subsequently the impacts projected to occur to natural and managed systems (Pierce et al. 2012).

GCMs have a proven ability to simulate the influence of increased greenhouse gas emissions on global and continental temperature trends (IPCC 2007), demonstrating that climate models are doing pretty well at capturing the dynamics of the climate system despite the aforementioned uncertainties. However, climate models are less successful in simulating observations at smaller geographic scales.

DOWNSCALING. Because adaptation measures are often most successful at a regional level, global climate output from GCMs must be translated into regional terms to aid decision making. A key problem in applying global data to regional scales is that at smaller scales the internal (natural) variability in the climate system has a greater influence than climate change. As an example, in the mid-latitudes—which encompass the Southwest—this natural variability is especially pronounced and is greater than observed and projected precipitation signals (Hawkins and Sutton 2009).

Translating global climate data into regional information can be accomplished through the process of *downscaling*. Simply, downscaling merges large-scale climate information from GCMs with local physical controls (such as mountain ranges, deserts, water bodies, or large urban areas) on climate. The two methods of downscaling are statistical and dynamical, and both have different strengths and weaknesses (Fowler, Blenkinsop and Tebaldi 2007). Statistical downscaling relates the GCM temperature and precipitation output to the observed small-scale variability in a given grid cell. These techniques are computationally efficient and permit downscaling of many global climate projections at a given location, but assume that the relationship between large-scale circulation and local surface climate does not change through time, even as the large-scale climate changes. Dynamical downscaling uses regional climate models (RCMs) to simulate small-scale processes, and resolve data at a higher spatial resolution. The downside is that these techniques require significant computing power. Thus, the choice of which downscaling method to use in developing regional projections involves tradeoffs between model output that is meaningful for local impact assessment and yet can still be performed in a mathematically efficient manner, given computational limitations. (See further discussion of downscaling in Chapter 6, Section 6.1).

In the present assessment, different downscaling methods are referenced in different chapters. Thus, understanding the tradeoffs and inherent uncertainties associated with each technique, as they apply to the Southwest, is important. For example, while the Rocky Mountains reach elevations over 14,000 feet and play an important role in influencing regional and local climatology, in GCMs (such as the NCAR Community Climate System Model 3.0[i]), the elevation of the mountains is represented as about 8,000

Box 19.1

Treatment of Uncertainty in the Southwest Assessment Report

Critical questions or problems related to climate change are included in this report as "key findings." For each key finding, the scientific team evaluated the body of scientific information and described the type of information used, the standards of evidence applied (noting the amount, quality, and consistency of evidence), the uncertainty associated with any results, and the degree of confidence in the outcome. This process constitutes a "traceable account" of the authors' reasoning and evidence. The uncertainty and confidence associated with each finding is an important component in assessing risk.

For findings that identify outcomes with potential high consequences (see guidance on risk-based framing in Chapter 2), uncertainty is estimated probabilistically. Probabilities are expressed as the likelihood that a particular outcome could occur under a given condition or scenario. Likelihoods are based on quantitative methods—such as model results or statistical sampling—or on expert judgment. In some cases, authors used standardized ranges:

Qualitative Language	Quantitative Language
More than a 9 in 10 chance	Greater than 95% likely
More than a 6 in 10 chance	Greater than 66% likely
About a 5 in 10 chance	Between 33% and 66% likely
Less than a 4 in 10 chance	Less than 33% likely
Almost no chance	Less than 5% likely

Wherever possible, the authors used quantitative estimates and describe consequential outliers that may fall outside a statistical confidence interval of 90% (which increases the reliability of a dataset).

The authors also assessed the degree of confidence (high, medium-high, medium, medium-low, or low) by considering the quality of the evidence and the level of agreement among experts with relevant knowledge and experience (Mastrandrea et al. 2010; Mastrandrea et al. 2011). Confidence is a subjective judgment, but it is based on systematic, transparent evaluation of the type, amount, quality, and consistency of evidence, and the degree of agreement among experts.

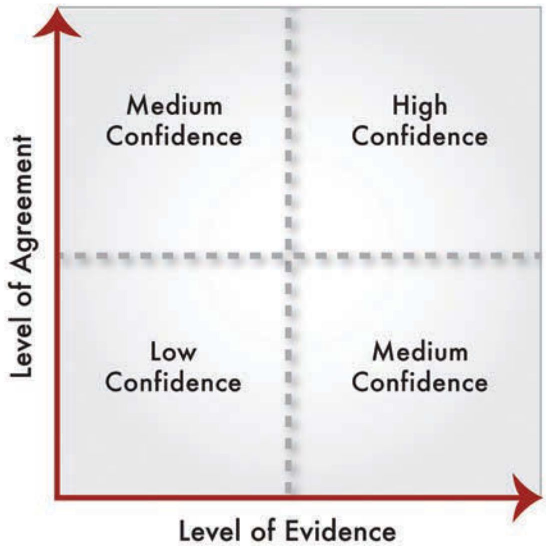

Figure 19.2 Summary evaluation of confidence, in terms of levels of evidence and agreement of the evidence. Adapted from Mastrandrea et al. (2011).

feet. In regional climate models (such as the Weather Research and Forecasting Model, or WRF[ii]) the mountains are represented as over 10,000 feet. The difference is because the topography must be simplified for global models and because of different model resolutions.[iii] Although the mountains are better represented in the RCMs, their higher resolution requires more intensive computational resources, which, in a practical sense, means that the RCMs are only able to utilize the inputs from a subset of the twenty-two available GCMs. Clearly, more data would be gained by using a larger suite (number) of GCMs, yet GCMs alone cannot account adequately for the important role of topography in the Intermountain West. The GCMs used in the IPCC's Fourth Assessment Report have a weak but systematic bias for overestimating the speed of upper-level westerly winds near 30°N and November-to-April precipitation in the Southwest. Of relevance is that the wettest models project the greatest drying in this region with climate change. As it turns out, all of these models have "subdued" topography that may contribute to the zonal wind bias and may also underestimate rain shadow effects, producing wet biases on the lee side of the mountains (McAfee, Russell, and Goodman 2011). Thus, in this case, the tradeoff between statistical and dynamical downscaling involves either a greater range of potential futures (which is valuable in planning and risk-based management) or potentially more accurate representation of climate.

DIRECT IMPACTS. Regional climate projections from downscaling are in turn used to drive other models of the physical environment. In the Southwest, water is a critical component of climate. Therefore, assessments typically must translate future climate projections into impacts on the region's hydrologic processes (such as precipitation, snowmelt runoff, streamflow, infiltration, groundwater recharge and discharge, evapotranspiration, and so on). Simulation models are often used for this task, with most of the effort spent characterizing future weather conditions that are consistent with climate projections. Those weather conditions are then used to simulate hydrologic processes. The hydrologic model itself is typically developed and verified under historical climate and watershed conditions. Uncertainty in projecting hydrologic processes arises from how the hydrologic model is structured, the way future weather over the watershed is characterized (which often requires some blending of historical weather observations and projected changes in climate), and assumptions about other features of a watershed that might change as climate changes and affects runoff. (See also the discussion presented in Chapter 10, especially in Section 10.3 and in "Planning Techniques and Stationarity" in Section 10.5.)

Despite limitations associated with such hydrologic models, outputs from these models are most influenced by the choice of GCM used to provide input, followed by the type of downscaling method used, then by the hydrologic model chosen (Wilby and Harris 2006; Crosbie, McCallum and Walker 2011). This suggests that GCMs and the level of understanding of large-scale processes are the largest source of uncertainties in the model uncertainty typology continuum discussed earlier. Given that outputs based on the averaging of results of numerous models are better than those based on the results of an individual model (Reichler and Kim 2008), impact studies that are informed by multiple global climate models will have a greater certainty than those based on a single global model.

Box 19.2

Case Study 1: Denver Water: Addressing Climate Change through Scenario Planning

Denver Water serves a growing population of customers and prepares long-range plans for meeting future water needs. Historical streamflow and weather records plus paleohydrologic data have been key information in projecting future water supply and demand conditions. Climate change fundamentally challenges the concept that the weather and hydrologic patterns of the past are the best representation of future conditions (Milly et al. 2008). But, there is a lot of uncertainty about how the climate will change. In addition to climate, other key uncertainties in long-range water planning include possible economic, regulatory, social, and demographic changes. Denver Water now uses scenario-planning techniques to try to prepare for these future uncertainties.

The "cone of uncertainty" (Figure 19.3) illustrates the growing uncertainty of future conditions over time. Scenarios are created to try to represent a plausible range of future conditions. Plans are created to meet each scenario, and common near-term strategies across plans are identified. "Decision points" note when strategy diverges from the common path. The goal is to take actions today that prepare for a range of future conditions. Maintaining flexibility and adaptability as well as identifying and preserving options are key elements in successfully preparing for future uncertainties such as climate change.

As a first step in climate change adaptation, Denver Water is testing the implications of a simple 5°F (3°C) temperature increase. Initial results show major supply losses and demand increases. Additional climate change conditions will be evaluated in an effort to develop a robust adaptation plan.

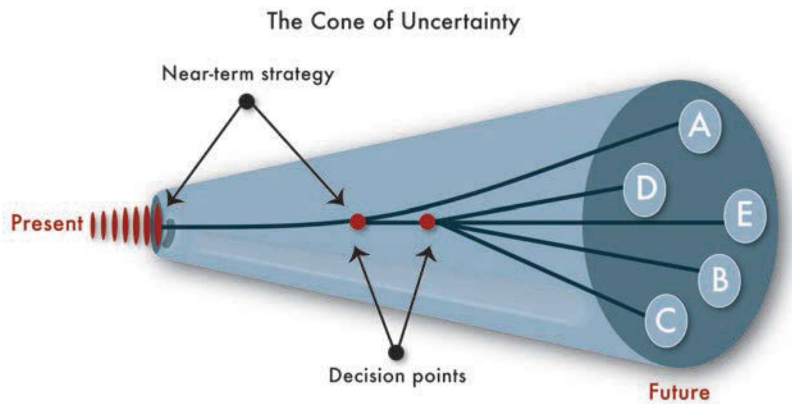

Figure 19.3 Cone of uncertainty used in Denver Water Scenario Planning Initiative. Uncertainties, due to knowledge or communication gaps or imperfect information increase as time progresses from present to future. The increase in uncertainties related to scientific understanding of the distant future (around 100 years hence), has prompted many resource managers and planners to consider multiple scenarios of the future, which can be evaluated at key decision points in the near or medium term (roughly 10-50 years into the future). Adapted from Waage and Kaatz (2011).

Box 19.3

Case Study 2: The National Park Service—Exploring Climate Futures and Decision Making in the Mojave Desert

Resource management decisions must be based on future expectations. However, in an era of rapid climate change, the future will be characterized by highly consequential and unprecedented changes that cannot be fully predicted. In February 2011, the National Park Service (NPS) convened a workshop to explore scenario planning as an approach for science-based decision making in the face of uncertainty for Southwestern parks and conservation areas.

Since 2007, the National Park Service has worked with other federal, state, and academic partners to develop a user-driven approach to build scenarios as a long-range planning tool for incorporating climate change into a range of NPS management processes and documents. The purpose is to better acquaint decision makers with climate complexity and uncertainty, evaluate management options, and ultimately implement effective, science-based decisions. The approach requires participation and transparency, and is structured in a way that encourages end-user input and ownership throughout the process. In addition to including climate-change information, the NPS scenario development process explores other external factors that define a park's operational environment, such as leadership and public values.

The February 2011 training workshop included scientists from the University of Arizona and other academic and governmental organizations, along with managers from the National Park Service, Bureau of Land Management, and Bureau of Reclamation. Participants explored how climate change could impact arid lands in the desert Southwest, using the Mojave Desert as a case study. Impacting factors that were considered to be uncertain but consequential included changes in precipitation, frequency of extreme storm events, extreme temperature events, duration and frequency of droughts, as well as societal concerns about these issues and leadership's capacity to implement adaptive measures. From these biophysical and sociopolitical drivers, participants created four plausible futures (scenarios) to test management and public response. Discussions centered on multiple pressures converging in the Southwest: public expectations for services such as water and renewable energy development, along with habitat connectivity (the interconnection of different habitats to allow species movement) and ecosystem resiliency as climate change forces species to move and adapt. Consensus emerged that future desert conservation efforts should be collaborations that are broad-based, landscape-scale, and multi-jurisdictional.

SOCIO-ECONOMIC IMPACTS. In a risk-based framework (planning based on the pros and cons of a given set of possibilities), decision makers are interested in the socio-economic impacts associated with different scenarios. However, socio-economic impacts encompass the entire sum of uncertainties in each step along the climate continuum (Figure 19.1). These impacts are also represented as being constant, whereas in reality, regulatory, institutional, and legislative policies change over time. In essence, decision making and the capacity to act are key elements of the uncertainty associated with socio-economic impact projections.

Communication uncertainties

COGNITIVE BARRIERS. The various uncertainties outlined above set up a number of analytic uncertainties and ultimately different interpretations about the results. Even if our understanding of climate science were 100% certain, science does not exist in a vacuum. Societal and individual perspectives are all molded by experiences and this affects the production of scientific information and its use to make decisions.

For example, climate scientists may choose from many different climate scenarios and models and tend to exhibit overconfidence in their results (see CCSP 2009). On the other hand, most people are psychologically distant from the concept of climate change. Not only must one sort through pervasive images of penguins and polar bears to rationally consider the problem, but the timeline for the onset of tangible impacts tends to be beyond most people's lifetimes. The decision-making public also often has many other interests—such as economic vitality, public health, and safety—that may have a higher value than concerns about climate change. Taken together, these factors can hinder the incorporation of climate information in planning and management.

The complexity of the connections and feedbacks in the climate system make bridging this gap difficult but not impossible. As examples, the nonlinear relationship between GHG emissions and atmospheric concentrations, or the reasons why a single winter storm does not invalidate the scientific perception that the global climate is warming, can be conveyed and understood through effective communication and mental models (Sterman 2008). Whether improved climate education will change perceptions about the utility of climate information is unclear (see, for example, Boykoff 2011; McCright 2011), but there are indications that improving understanding of the climate and the uncertainties inherent in climate projections may facilitate the inclusion of climate information in planning and management (Pidgeon and Fischhoff 2011).

19.3 Confidence and Uncertainty

Scientists use a variety of tactics to express scientific uncertainty. In general, people are familiar with probabilities and odds, which quantify the likelihood of an outcome. But uncertainty is more nuanced in an assessment where a large body of work is being represented. Unfortunately, the labels "likely" and "unlikely" to indicate the probability of occurrence of an event are interpreted very differently by different people and therefore do not always effectively communicate risk (see CCSP 2009). Recognizing this, in 2001 the IPCC implemented uncertainty guidelines for the use of such language into its assessment process. The intention of the guidelines is to convey the amount of evidence (uncertainty) and degree of consensus (confidence) about climate information (Moss and Schneider 2000). These uncertainty standards were modified slightly for the IPCC's Fourth Assessment Report (Manning et al. 2004; IPCC 2007). The 2000 U.S. National Climate Assessment adopted similar uncertainty standards and language to the IPCC (National Assessment Science Team 2001); the uncertainty language was altered again for the U.S. Global Change Research Program (USGCRP) synthesis and assessment products (CCSP 2009; Karl, Melillo and Peterson 2009). The IPCC has once again revamped its approach to uncertainty for its Fifth Assessment Report (Mastrandrea et al. 2010; Mastrandrea et al. 2011). The labeling conventions for uncertainty used in this report are modified from the current IPCC guidelines and outlined in Box 19.1.

Box 19.4

Case Study 3: Planning in the San Francisco Bay Using Sea-Level Rise Projections

The San Francisco Bay Conservation and Development Commission (SFBCDC), created in 1965 by the state of California, is "dedicated to the protection and enhancement of San Francisco Bay and to the encouragement of the Bay's responsible use." In an effort to update twenty-two-year-old sea-level data in the San Francisco Bay Plan, the SFBCDC commissioned a report to reevaluate sea-level-rise projections and its impact to the bay. The report concluded that sea level in the bay could rise 10 to 17 inches (26 to 43 cm) by 2050, 17 to 32 inches (43 to 81 cm) by 2070, and 31 to 69 inches (78 to 176 cm) by the end of the century (San Francisco Bay Conservation and Development Commission 2011). In October 2011, the SFBCDC approved these findings and incorporated the information into policies in the San Francisco Bay Plan, including future project designs, shoreline plans, and permit approvals. This new section details the impacts of climate change and, in particular, addresses issues regarding adaptation to sea-level rise. Policies in the plan specifically related to construction along vulnerable shorelines were changed to both promote habitat restoration and encourage building only in suitable regions of the bay.

19.4 What Is Known and Not Known About Climate in the Southwest

With few exceptions, there is now more evidence and more agreement among climate scientists about the physical climate and related impacts in the Southwest than there was in the 2009 National Climate Assessment (Karl, Melillo, and Peterson 2009) (Table 19.1). The body of research about processes affecting both global and regional climate is growing, as are some observational datasets, allowing for the detection of trends. Uncertainty and confidence about climate fluctuates with the ebb and flow of new data. Sometimes as scientists learn more, they become more confident in findings. This is particularly true of studies that rely on observational data. For example, the long and continuous time series of streamflow data has allowed scientists to document the early onset of the peak spring season pulse of streamflow in the region. On the other hand, additional data and new observations can sometimes muddy the works, drawing previously held conclusions into question. As scientists learn more about the climate system and the factors that naturally impact it, other parameters about which scientists know relatively little can factor more prominently in discussions of uncertainties in predicting future changes.

The synthesis of the evolution of knowledge regarding climate changes and their impacts in the Southwest (Table 19.1) is drawn from the judgment of the authors of this assessement report. Statements included in Table 19.1 were quoted from the Southwest section of the 2009 National Climate Assessment (Karl, Melillo, and Peterson 2009). The authors of this chapter made no attempt to correct or update the statements extracted from the 2009 National Climate Assessment. For each statement from the 2009 National Climate Assessment, the author team of this report identified the relative change in level of agreement among scientists about the statement, and changes in the level of evidence available to evaluate the statements. The table can be used as a coarse baseline for evaluating the evolution of knowledge since the 2009 National Climate Assessment.

Table 19.1 Evolution of knowledge about climate in the Southwest

2009 Southwest Assessment	**This Assessment**							
	← Agreement →					← Evidence →		
	Much Less	Less	Same	More	Much More	Same	More	Much More
Human-induced climate change appears to be well underway in the Southwest. Recent warming is among the most rapid in the nation, significantly more than the global average in some areas.				X			X	
Projected declines in spring snowpack and Colorado River flow					X			X
Projections suggest continued strong warming					X			X
Projected summertime temperature increases are greater than the annual average increases in some parts of the region, and are likely to be exacerbated locally by expanding urban heat island effects					X			X
Further water cycle changes are projected, which, combined with increasing temperatures, signal a serious water supply challenge in the decades and centuries ahead.					X			X
Water supplies are projected to become increasingly scarce, calling for trade-offs among competing uses, and potentially leading to conflict.			X				X	
Water supplies in some areas of the Southwest are already becoming limited, and this trend toward scarcity is likely to be a harbinger of future water shortages.			X			X		
Limitations imposed on water supply by projected temperature increases are likely to be made worse by substantial reductions in rain and snowfall in the spring months, when precipitation is most needed to fill reservoirs to meet summer demand.			X			X		
Increased likelihood of water-related conflicts between sectors, states, and even nations			X			X		
Increasing temperature, drought, wildfire, and invasive species will accelerate transformation of the landscape.				X			X	

Table 19.1 Evolution of knowledge about climate in the Southwest (Continued)

2009 Southwest Assessment	This Assessment							
	← Agreement →					← Evidence →		
	Much Less	Less	Same	More	Much More	Same	More	Much More
Competing demands from [Native] treaty rights, rapid development, and changes in agriculture in the region, exacerbated by years of drought and climate change, have the potential to spark significant conflict over an already over-allocated and dwindling [water] resource.			X			X		
Climate change already appears to be influencing both natural and managed ecosystems of the Southwest.				X			X	
Future landscape impacts are likely to be substantial, threatening biodiversity, protected areas, and ranching and agricultural lands.				X			X	
Record wildfires are also being driven by rising temperatures and related reductions in spring snowpack and soil moisture.			X			X		
How climate change will affect fire in the Southwest varies according to location. In general, total area burned is projected to increase.			X			X		
Fires in wetter, forested areas are expected to increase in frequency, while areas where fire is limited by the availability of fine fuels experience decreases			X			X		
Climate changes could also create subtle shifts in fire behavior, allowing more "runaway fires"—fires that are thought to have been brought under control, but then rekindle.			X			X		
The magnitude of fire damages, in terms of economic impacts as well as direct endangerment, also increases as urban development increasingly impinges on forested areas.					X			X
Increasing temperatures and shifting precipitation patterns will drive declines in high-elevation ecosystems such as alpine forests and tundra.			X			X		
As temperatures rise, some iconic landscapes of the Southwest will be greatly altered as species shift their ranges northward and upward to cooler climates, and fires attack unaccustomed ecosystems which lack natural defenses.		X				X		
Increased frequency and altered timing of flooding will increase risks to people, ecosystems, and infrastructure.			X			X		

Table 19.1 Evolution of knowledge about climate in the Southwest (Continued)

2009 Southwest Assessment	This Assessment: Agreement					This Assessment: Evidence		
	Much Less	Less	Same	More	Much More	Same	More	Much More
Some species will move uphill, others northward, breaking up present-day ecosystems; those species moving southward to higher elevations might cut off future migration options as temperatures continue to increase.		X				X		
Potential for successful plant and animal adaptation to coming change is further hampered by existing regional threats such as human-caused fragmentation of the landscape, invasive species, river-flow reductions, and pollution.			X			X		
A warmer atmosphere and an intensified water cycle are likely to mean not only a greater likelihood of drought for the Southwest, but also an increased risk of flooding.			X			X		
More frequent dry winters suggest an increased risk of these [water] systems running short of water.			X			X		
A greater potential for flooding also means reservoirs cannot be filled to capacity as safely in years where that is possible. Flooding also causes reservoirs to fill with sediment at a faster rate, thus reducing their water-storage capacities.			X			X		
Rapid landscape transformation due to vegetation die-off and wildfire as well as loss of wetlands along rivers is also likely to reduce flood-buffering capacity.			X			X		
Increased flood risk in the Southwest is likely to result from a combination of decreased snow cover on the lower slopes of high mountains, and an increased fraction of winter precipitation falling as rain and therefore running off more rapidly.					X			X
Increase in rain on snow events will also result in rapid runoff and flooding.			X			X		
Impact of more frequent flooding is a greater risk to human beings and their infrastructure. This applies to locations along major rivers, but also to much broader and highly vulnerable areas such as the Sacramento–San Joaquin River Delta system.				X			X	
Projected changes in the timing and amount of river flow, particularly in winter and spring, is estimated to more than double the risk of Delta flooding events by mid-century, and result in an eight-fold increase before the end of the century.				X			X	

Table 19.1 Evolution of knowledge about climate in the Southwest (Continued)

2009 Southwest Assessment	This Assessment							
	← Agreement →					← Evidence →		
	Much Less	Less	Same	More	Much More	Same	More	Much More
Efforts are underway to identify and implement adaptation strategies aimed at reducing these risks [to the Delta and Suisun Marsh].			X			X		
Unique tourism and recreation opportunities are likely to suffer.			X			X		
Increasing temperatures will affect important winter activities such as downhill and cross-country skiing, snowshoeing, and snowmobiling, which require snow on the ground.				X			X	
Projections indicate later snow and less snow coverage in ski resort areas, particularly those at lower elevations and in the southern part of the region.				X			X	
Decreases from 40% to almost 90% are likely in end-of-season snowpack under a higher emissions scenario in counties with major ski resorts.			X			X		
Earlier wet snow avalanches—more than six weeks earlier by the end of this century under a higher emissions scenario—could force ski areas to shut down affected runs before the season would otherwise end.			X			X		
Ecosystem degradation will affect the quality of the experience for hikers, bikers, birders, and others.				X			X	
Water sports that depend on the flows of rivers and sufficient water in lakes and reservoirs are already being affected, and much larger changes are expected.			X			X		
Agriculture faces increasing risks from a changing climate.				X			X	
Urban areas are also sensitive to temperature-related impacts on air quality, electricity demand, and the health of their inhabitants.				X		X		
The magnitude of projected temperature increases for the Southwest, particularly when combined with urban heat island effects for major cities such as Phoenix, Albuquerque, Las Vegas, and many California cities, represent significant stresses to health, electricity, and water supply in a region that already experiences very high summer temperatures.				X		X		

Table 19.1 Evolution of knowledge about climate in the Southwest (Continued)

2009 Southwest Assessment	This Assessment: ← Agreement →					← Evidence →		
	Much Less	Less	Same	More	Much More	Same	More	Much More
Rising temperatures also imply declining air quality in urban areas such as those in California which already experience some of the worst air quality in the nation.				X		X		
With more intense, longer-lasting heat wave events projected to occur over this century, demands for air conditioning are expected to deplete electricity supplies, increasing risks of brownouts and blackouts.				X			X	
Electricity supplies will also be affected by changes in the timing of river flows and where hydroelectric systems have limited storage capacity and reservoirs.				X			X	
Agriculture will experience detrimental impacts in a warmer future, particularly specialty crops in California such as apricots, almonds, artichokes, figs, kiwis, olives, and walnuts.				X			X	
Accumulated winter chilling hours have already decreased across central California and its coastal valleys. This trend is projected to continue to the point where chilling thresholds for many key crops would no longer be met.				X			X	
California's losses due to future climate change are estimated between 0% and 40% for wine and table grapes, almonds, oranges, walnuts, and avocadoes, varying significantly by location.			X			X		
Adaptation strategies for agriculture in California include more efficient irrigation, which has the potential to help compensate for climate-driven increases in water demand for agriculture due to rising temperatures.	X						X	
Adaptation strategies for agriculture in California include shifts in cropping patterns, which have the potential to help compensate for climate-driven increases in water demand for agriculture due to rising temperatures.				X			X	

Note: To construct this table, the authors of this chapter quoted statements from the Southwest section of 2009 National Climate Assessment (Karl, Melillo and Peterson 2009). For each statement, the authors of this report identified the relative change in level of agreement among scientists about the statement, and changes in the pertinent level of evidence, based on the current assessment of climate in the Southwest.

Table 19.2 presents an assessment of knowledge gaps and scientific challenges related to improving the understanding of physical and biological processes, impacts, vulnerabilities and societal responses to climate change. The authors of this report identified knowledge gaps and uncertainties, and the authors of this chapter evaluated and classified the information into key challenges. In each key challenge area, the knowledge gaps are divided into the three categories of uncertainty, as follows: model uncertainties (those related to understanding and modeling physical and biological processes and phenomena), scenario uncertainties (those related to identifying vulnerabilities, mitigation and adaptation choices), and communication uncertainties (those related to the effective exchange of knowledge between scientists and decision makers). Table 19.2 can be used as a coarse baseline for understanding sources of uncertainty related to climate and adaptation science challenges, and to inform future research priorities.

Table 19.2 Knowledge gaps and key challenges to improving understanding, reducing uncertainty, identifying and addressing vulnerabilities to climate changes in the Southwest

	Model Uncertainty				**Scenario Uncertainty**				
Knowledge Gaps Contributing to Key Challenges	Observational Data	Understanding Physical Climate Dynamics	Climate Models & Downscaling	Physical Climate Impacts to Biological & Human Systems	Social & Behavioral Factors	Economic Factors	Policy & Regulatory Factors	Communication & Education	**Chapter(s)**
KEY CHALLENGE: There is a dearth of climate observations at high elevations and on tribal lands in the Southwest.									
Changes in weather and climate observations, variability, and trends across mountain gradients and at variable elevations, including representation of topography in climate models	X	X	X						Present Weather and Climate: Average Conditions (4) Present Weather and Climate: Evolving Conditions (5) Water: Impacts, Risks, and Adaptation (10) Coastal Issues(9)
Weather and climate observations, variability, and trends on tribal lands	X								Present Weather and Climate: Average Conditions (4) Unique Challenges Facing Southwestern Tribes (17)

Table 19.2 Knowledge gaps and key challenges to improving understanding, reducing uncertainty, identifying and addressing vulnerabilities to climate changes in the Southwest (Continued)

	Model Uncertainty				**Scenario Uncertainty**				
Knowledge Gaps Contributing to Key Challenges	Observational Data	Understanding Physical Climate Dynamics	Climate Models & Downscaling	Physical Climate Impacts to Biological & Human Systems	Social & Behavioral Factors	Economic Factors	Policy & Regulatory Factors	Communication & Education	**Chapter(s)**
Measurements of precipitation amount and type	X								Present Weather and Climate: Average Conditions (4) Present Weather and Climate: Evolving Conditions (5) Future Climate: Projected Average (6)
KEY CHALLENGE: There is limited understanding of the influence of climate change on natural variability (e.g. ENSO, PDO), extreme events (droughts, floods), and the marine layer along coastal California.									
Ability to connect climate change and extreme events		X							Human Health (15)
Understanding of physical processes such as atmospheric convection, evapotranspiration, snow pack formation, and runoff production		X							Present Weather and Climate: Evolving Conditions (5)
Connections between modes of natural variability (ENSO and PDO) and climate change; including effect on SW Monsoon		X							Future Climate: Projected Extremes (7) Future Climate: Projected Average (6) Water: Impacts, Risks, and Adaptation (10)
Occurrence of compound high-impact extremes such as drought and heat waves		X							Future Climate: Projected Extremes (7)
Understanding of marine layer processes		X							Coastal Issues (9)

Table 19.2 Knowledge gaps and key challenges to improving understanding, reducing uncertainty, identifying and addressing vulnerabilities to climate changes in the Southwest (Continued)

	Model Uncertainty				Scenario Uncertainty				
Knowledge Gaps Contributing to Key Challenges	Observational Data	Understanding Physical Climate Dynamics	Climate Models & Downscaling	Physical Climate Impacts to Biological & Human Systems	Social & Behavioral Factors	Economic Factors	Policy & Regulatory Factors	Communication & Education	**Chapter(s)**
KEY CHALLENGE: Climate models, downscaling and resulting projections of the physical climate are imperfect. Representing the influence of the diverse topography of the Southwest on regional climate is a particular challenge.									
Downscaling methodologies and inconsistencies			X					X	Water: Impacts, Risks, and Adaptation (10)
Reproducibility of extreme high-frequency precipitation events by climate models			X						Future Climate: Projected Extremes (7)
KEY CHALLENGE: The impacts of climate change on key components of the natural ecosystem (including species and land regimes) are ill constrained.									
Links between impacts and climate change				X					Unique Challenges Facing Southwestern Tribes (17)
Impacts to tribal lands and societies				X					Unique Challenges Facing Southwestern Tribes (17)
Relationship between climate and distributions of species				X					Natural Ecosystems (8)
Connections between climate and disease systems				X					Human Health (15)
Response of individual species to changes in climate				X					Natural Ecosystems (8)
Extent to which individuals in different populations or species can observably change physical characteristics in response to climate				X					Natural Ecosystems (8)

Table 19.2 Knowledge gaps and key challenges to improving understanding, reducing uncertainty, identifying and addressing vulnerabilities to climate changes in the Southwest (Continued)

	Model Uncertainty				Scenario Uncertainty				
Knowledge Gaps Contributing to Key Challenges	Observational Data	Understanding Physical Climate Dynamics	Climate Models & Downscaling	Physical Climate Impacts to Biological & Human Systems	Social & Behavioral Factors	Economic Factors	Policy & Regulatory Factors	Communication & Education	**Chapter(s)**
Range of potential rates of evolution of individual populations or species				X					Natural Ecosystems (8)
Extent to which phenological events among species that interact will become asynchronous				X					Natural Ecosystems (8)
Effect of climate change on "dryland" production -- primarily dryland grain production in Colorado and Utah and forage production throughout the Southwest				X					Agriculture and Ranching (11)
Ecosystem responses (e.g., sensitivity, adaptive capacity) as water types (e.g. snow v. rain), water quantities, water quality, and water management practices change				X			X		Natural Ecosystems (8) Climate Change and U.S.-Mexico Border Communities (16)
KEY CHALLENGE: The adaptive capacity of decision-making entities and legal doctrines to handle climate impacts is unclear. This creates a challenge for identifying vulnerabilities to climate in the Southwest.									
Ability of the transportation system to manage large disruptions					X	X			Transportation (14)
Sensitivity and adaptive capacity of border communities to climate change impacts				X	X				Climate Change and U.S.-Mexico Border Communities (16)
Sensitivity and adaptive capacity of border agriculture and ranching sector to a range of stressors					X				Climate Change and U.S.-Mexico Border Communities (16)
Capacity of water infrastructure to address changes					X		X		Water: Impacts, Risks, and Adaptation (10)

Table 19.2 Knowledge gaps and key challenges to improving understanding, reducing uncertainty, identifying and addressing vulnerabilities to climate changes in the Southwest (Continued)

	Model Uncertainty				Scenario Uncertainty				
Knowledge Gaps Contributing to Key Challenges	Observational Data	Understanding Physical Climate Dynamics	Climate Models & Downscaling	Physical Climate Impacts to Biological & Human Systems	Social & Behavioral Factors	Economic Factors	Policy & Regulatory Factors	Communication & Education	**Chapter(s)**
Economic status of urban public works departments and ability to reduce flood risk						X			Urban Areas (13)
Fiscal capacity of cities to respond rapidly and effectively to climate change challenge						X			Urban Areas (13) Transportation (14)
Regulatory capacity to address climate adaptation and mitigation							X		Coastal Issues (9)
Capacity and flexibility of water and land regulations, agreements and legislation to accommodate climate adaptation and planning							X		Water: Impacts, Risks, and Adaptation (10) Agriculture and Ranching (11) Unique Challenges Facing Southwestern Tribes (17)
Financial risk to property						X			Coastal Issues (9)
KEY CHALLENGE: Regulation, legislation, political and social responses to climate all play an important role in our ability to adapt to climate impacts and mitigate greenhouse gas emissions.									
How the current and future fleet of power plants will evolve, particularly with respect to utilized fuel type and impacts on GHG emissions					X	X	X		Energy: Supply, Demand, and Impacts (12) Transportation (14)
The type and intensity of fuels used in the transportation sector and impacts on GHG emissions					X	X	X		Energy: Supply, Demand, and Impacts (12) Transportation (14)
Social and political responses to climate change; including market incentives					X	X	X	X	Coastal Issues (9)
Communication between planners and academics					X			X	Coastal Issues (9)

Table 19.2 Knowledge gaps and key challenges to improving understanding, reducing uncertainty, identifying and addressing vulnerabilities to climate changes in the Southwest (Continued)

	Model Uncertainty				**Scenario Uncertainty**				
Knowledge Gaps Contributing to Key Challenges	Observational Data	Understanding Physical Climate Dynamics	Climate Models & Downscaling	Physical Climate Impacts to Biological & Human Systems	Social & Behavioral Factors	Economic Factors	Policy & Regulatory Factors	Communication & Education	**Chapter(s)**
Extent of upper-level and/or grass roots leadership to effect change					X		X		Urban Areas (13)
Socio-economic and political conditions						X	X		Unique Challenges Facing Southwestern Tribes (17)
City-scale decisions about adaptation and regulatory frameworks					X		X		Urban Areas (13)
Environmental and economic impacts of extensive water transfers and effect on agriculture						X	X		Agriculture and Ranching (11)
Agricultural and environmental policies							X		Agriculture and Ranching (11)
Effect of water availability (physical and legal) on agriculture output				X			X		Agriculture and Ranching (11)
National policies related to air quality standards							X		Human Health (15)
Understanding of how adaptation to climate change develops and functions is limited, as is the role played by institutions in promoting effective adaptation							X	X	Climate Change and U.S.-Mexico Border Communities (16)
KEY CHALLENGE: Climate change is a multi-stressor problem, and many factors are at play. In the Southwest, population growth is particularly important.									
Future demand for energy; including temporal and spatial shifts					X	X	X		Energy: Supply, Demand, and Impacts (12)
Age distribution in the population					X				Transportation (14)

Table 19.2 Knowledge gaps and key challenges to improving understanding, reducing uncertainty, identifying and addressing vulnerabilities to climate changes in the Southwest (Continued)

	Model Uncertainty				Scenario Uncertainty				
Knowledge Gaps Contributing to Key Challenges	Observational Data	Understanding Physical Climate Dynamics	Climate Models & Downscaling	Physical Climate Impacts to Biological & Human Systems	Social & Behavioral Factors	Economic Factors	Policy & Regulatory Factors	Communication & Education	**Chapter(s)**
Global and U.S. economic outlook						X			Transportation (14)
Global and U.S. manufacturing and industrial patterns						X			Transportation (14)
The extent to which heat-related morbidity and mortality are a multi-stressor problem						X			Human Health (15)

Note: To construct this table, the authors of each chapter in this report identified key knowledge gaps and uncertainties. For Chapters 3–8, authors, outlined the major elements needed to improve confidence in observed and projected climate trends. For Chapter 9–18, author teams identified factors and knowledge gaps that need to be addressed in order to improve the ability of the respective sector to identify vulnerabilities and/or adaptive responses. The author team for this chapter identified Key Challenges based on common themes in the compilation of inputs from different chapters.

19.5 Moving Forward

Climate projections can provide information for understanding risks associated with physical, biological, and social impacts. Although model projections are imperfect given the uncertainties outlined above, entities in the Southwest are moving forward and using innovative strategies to incorporate climate information in their planning and management schemes.[v] Both public and private planners are employing strategies that run the gamut from iterative risk management frameworks (which adapt management strategies to new information and changing circumstances) to resilience strategies (which enhance the capacity to withstand and recover from emergencies and disasters) to approaches that optimize for a particular desired set of conditions (NRC 2011). Case studies from the Southwest are highlighted throughout this chapter.

Box 19.5

Case Study 4: Transmission Planning in the Western States

Resource management decisions must be based Western governors have long identified clean, diverse, and reliable energy as a regional and national priority. But access to transmission lines is a significant impediment to increasing renewable resources as a portion of the overall energy portfolio. There is also a broad recognition of the need to consider water, land use, and wildlife when planning and developing energy supplies in the West. To address these issues, the Western Governors' Association and the Western States Water Council are collaborating with the Department of Energy and the National Laboratories on the Regional Transmission Expansion Project (RTEP). A major focus of the project is to seek generation and transmission options that are compatible with reliable water supplies and healthy wildlife communities in the West (Iseman and Schroder 2012).

Electricity generation and reliability of the grid are dependent on availability of water resources. Most of the power generated in the West requires water, and in order to move electricity to population centers, transmission lines need to be sited near these power plants. Even low-carbon electricity portfolios require additional water supplies. Consequently, the reliability of the grid and electricity supplies depends on the availability of water.

To make better decisions on energy and water, risks associated with a variable water supply must be considered. Drought has always been a fact of life in the arid West. Thus, considering drought in this planning effort is prudent in order to minimize risks to both the grid and water supplies. However, projections of drought in the short term (less than fifty years) are uncertain. Long-term climate projections indicate there will potentially be more severe drought events; but in the short term, natural variability trumps climate change.

To address risks posed by drought, the RTEP team is using past droughts to test the vulnerability to dry conditions of proposed transmission systems. These droughts are not necessarily those recorded in the observation records, but rather paleodroughts that occurred up to 1,000 years ago, as evidenced by tree rings in the region.

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Endnotes

i See http://www.cesm.ucar.edu/models/ccsm3.0.

ii See http://wrf-model.org.

iii Grid boxes are 100 miles on each side in the GCM, compared with 30 miles square in the RCM (with more than a ten-fold increase in resolution).

iv See San Francisco Bay Plan, http://www.bcdc.ca.gov/laws_plans/plans/sfbay_plan. Since its original adoption in 1968, the plan has been amended as warranted by new data, including in October 2011, as explained in the text.

v Climate projections based on scenarios of future emissions are inherently uncertain. Climate models were initially built as experiments intended to facilitate understanding of the physical processes driving climate systems—not to predict specific, optimal outcomes. Rather, projections emerging from climate models can provide suites of potential futures. At this point, even significant investment in computational models may not significantly increase the certainty of climate projections. However, despite their uncertainties, climate model outputs are being incorporated into decision making processes in different sectors, at different geographic scales, across the Southwestern US. Simply, uncertainty related to future climate (whether physical, biological, or regulatory) is not impeding the use of climate information in decision making.