Chapter 20

Research Strategies for Addressing Uncertainties

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Executive Summary

There is an immense volume of information pertaining to research needs for addressing climate change uncertainties and resolving key information gaps. Fortunately, multiple independent efforts to establish research *priorities* have yielded similar results. Input on research needs is being used to craft national scientific priorities and strategies that are being implemented regionally by agencies and organizations. A number of regionally based efforts are already underway to aggregate and synthesize climate-related management needs and research priorities. Landscape Conservation Cooperatives and Climate

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Science Centers, funded by the Department of the Interior, are conducting strategic syntheses of common resource-management priorities and related science needs across the Southwest, and many of these priorities and needs are related to climate variability and change.

The present Assessment includes many examples of the types of research that are needed to address key climate science uncertainties. The Assessment also includes examples of information needs related to understanding climate effects on systems (human, biophysical, ecosystems, and others) in the Southwest. Implementation of research strategies will increase understanding and improve the ability of the scientific community to anticipate the direction or magnitude of future climate-related change in these systems. The assembly of experts for the other chapters of this document provided a unique opportunity to draw upon the authors' collective expertise to share knowledge about priority research strategies. The peer-reviewed information sources assessed in this chapter highlight research strategies and priorities established by the research community. Other sources cover priorities that are based primarily on management and policy needs. In the latter type, the sources represent the consensus of senior leaders of organizations, generally with substantial input and advice from the organizations' technical and scientific experts.

20.1 Introduction

This chapter examines research strategies that aim to reduce uncertainty associated with climate drivers and their effects on systems in the Southwest. It also identifies scientific approaches that are being considered for implementation in programs of adaptive responses to climate change. This chapter was written collaboratively with Chapter 19, which outlines some of the most important uncertainties related to climate variability and change in the Southwestern United States. In these chapters the uncertainty derives from both our presently imperfect capability to model climate and other earth systems and from our inability to adequately characterize social, economic, policy and regulatory responses in the form of adaptation and mitigation.

Sources of information on research strategies infrequently utilize a risk-based perspective and usually do not incorporate a formal statistical definition of risk (Raiffa and Schlaiffer 2000). Although in this Assessment we utilize some sources that have undergone scientific peer review, others are heavily influenced by policy. In such cases, the products (which are often unpublished papers) represent the consensus of senior leaders of agencies and organizations (including inter-organizational and inter-agency collaboratives) who generally have received substantial input and advice from the organizations' and agencies' technical and scientific experts. In policy-influenced products, formal evaluations of confidence employing levels of evidence and agreement (e.g., Mastrandrea et al. 2010) are typically not undertaken or reported. Instead, the level of confidence expressed in these collaborative technical-policy products represents the judgment of high-level decision makers regarding alternative management approaches to adapt effectively to climate change. Thus, this chapter offers an opportunity for the findings of the *Assessment of Climate Change in the Southwest United States* that are associated with lower confidence or higher uncertainty (e.g., Moss and Yohe 2011) to be prioritized in planning future climate-effects research.

20.2 Developing Research Strategies from Information Needs

Raising confidence in research findings by increasing evidence and consensus (Chapter 19; Mastrandrea et al. 2010) often involves iterative and circuitous pathways that can affect both the amount of evidence and level of agreement, but may only infrequently address both together. Because formal determinations about confidence (see Figure 20.1) are rarely undertaken, uncertainty is generally only implicitly considered in determining information needs for climate-effects research. Nonetheless there are many fine examples linking information needs to research strategies. At a national scale, the U.S. Forest Service has used research needs to craft a scientific strategy and implementation plan to organize its climate-effects research along three themes: ecosystem sustainability (climate-change adaptation), carbon sequestration (climate-change mitigation), and decision support (USFS 2010). In the Southwest, the Forest Service Research and Development program is using these broad themes to implement its climate-change research program through its Pacific Southwest and Rocky Mountain Forest and Range research stations.

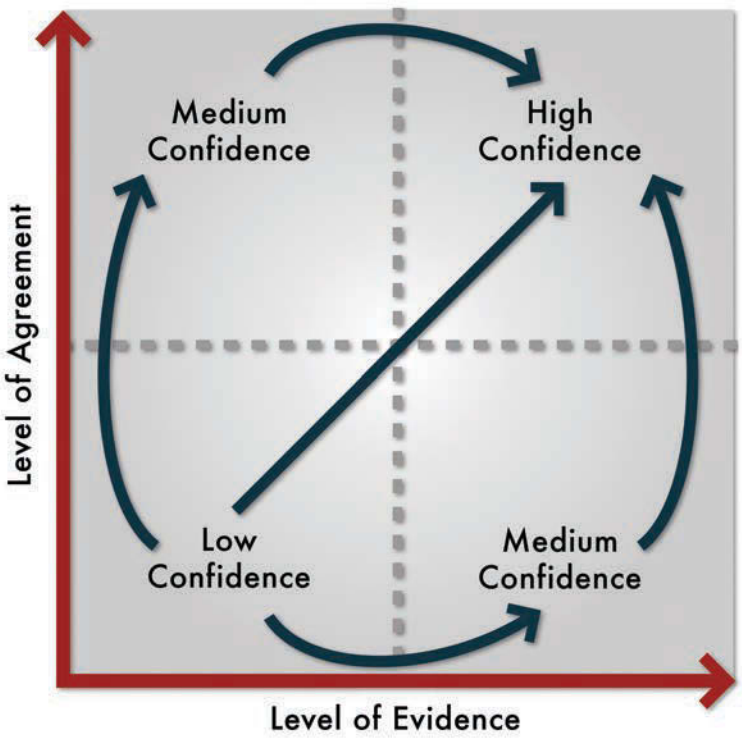

Figure 20.1 Research strategies for addressing uncertainties. Trajectories show how the level of evidence presented in climate effects research and agreement about the research, independently and collectively generate greater confidence in the research findings. Source: Mastrandrea et al. (2010), Mastrandrea et al. (2011).

Other national information needs and research priorities related to climate change have been developed (Lucier et al. 2006; DOE 2010; IWGCCH 2010; NRC 2010) along with syntheses of natural resource management-related gaps in scientific information pertaining to various regional resources and lands (California Coastal Commission 2008; BLM 2011; Brekke et al. 2011). However, climate-oriented scientific needs assessments are currently at an embryonic stage of development for the Southwest as a distinct region.

Within the Southwest, a number of efforts have been aggregating and synthesizing management needs and research priorities. For example, the Great Basin Research and Management Partnership[i] has been particularly active in developing momentum toward collaborative management and research (Chambers, Devoe and Evendon 2008). Climate variation is among the drivers of change considered in its work.

The Regional Integrated Sciences and Assessments (RISA) program, funded by the Climate Program Office at the National Oceanic and Atmospheric Administration (NOAA), was designed in part to enable NOAA to work with constituents to further its mission of climate science, monitoring, and data management. One of the Southwestern RISAs, the Western Water Assessment, has identified and characterized key people, projects, and documents related to climate in the state of Utah to provide guidance for research needs there.[ii]

The Department of the Interior's development of a nation-wide system of Regional Climate Science Centers (CSCs) represents a new approach to evaluate needs for scientific information about climate influences on natural and human resources at the regional scale, and to address such needs through collaborations of university and government research institutions (Salazar 2009). CSCs such as the Southwest Climate Science Center[iii] work with stakeholders throughout the Southwest to identify key scientific needs at the regional scale. Partner institutions such as NOAA's RISA program and the Forest Service Research and Development program will be important collaborators for the CSCs. The CSCs also are working with management-oriented inter-organizational groups, notably the Landscape Conservation Cooperatives (discussed below), which are being developed concurrently with the CSCs to help address the impacts of climate change on the nation's natural and cultural resources (Figure 20.2).

A number of factors can improve the dialogue about climate-effects research findings with those who are implementing climate mitigation and adaptation programs. Chief among these factors are:

- communication networks, science translation, and capacity for ongoing assessment;
- elimination of possible duplication and insufficient coordination of efforts among federal, state, and local agencies;
- improved access to climate change data and information; and
- improved understanding of the impact of laws and regulations on adaptation policy and implementation.

Research products will have more impact if such translational factors are considered as an essential part of strategy development rather than as an ancillary component. As

a changing climate necessitates novel demands on decision processes (NRC 2009), the process of strategy development can be optimized if institutions charged with making decisions about climate adaptation and mitigation are involved early on. Pilot efforts by the National Park Service to test scenario planning related to climate futures (Box 19.3) are an example of one approach that is proactively integrating managers' perspectives.

20.3 Research Strategies Derived from the Southwest Climate Assessment

The assembly of experts for the *Assessment of Climate Change in the Southwest United States* presented a unique opportunity to draw upon the authors' collective expertise to outline uncertainty (see Chapter 19) and evaluate research-strategy priorities from a scientific perspective. A summary of strategies to address gaps in knowledge and data, monitoring needs, and modeling and other deficiencies that are outlined throughout this Assessment are presented in Table 20.1.

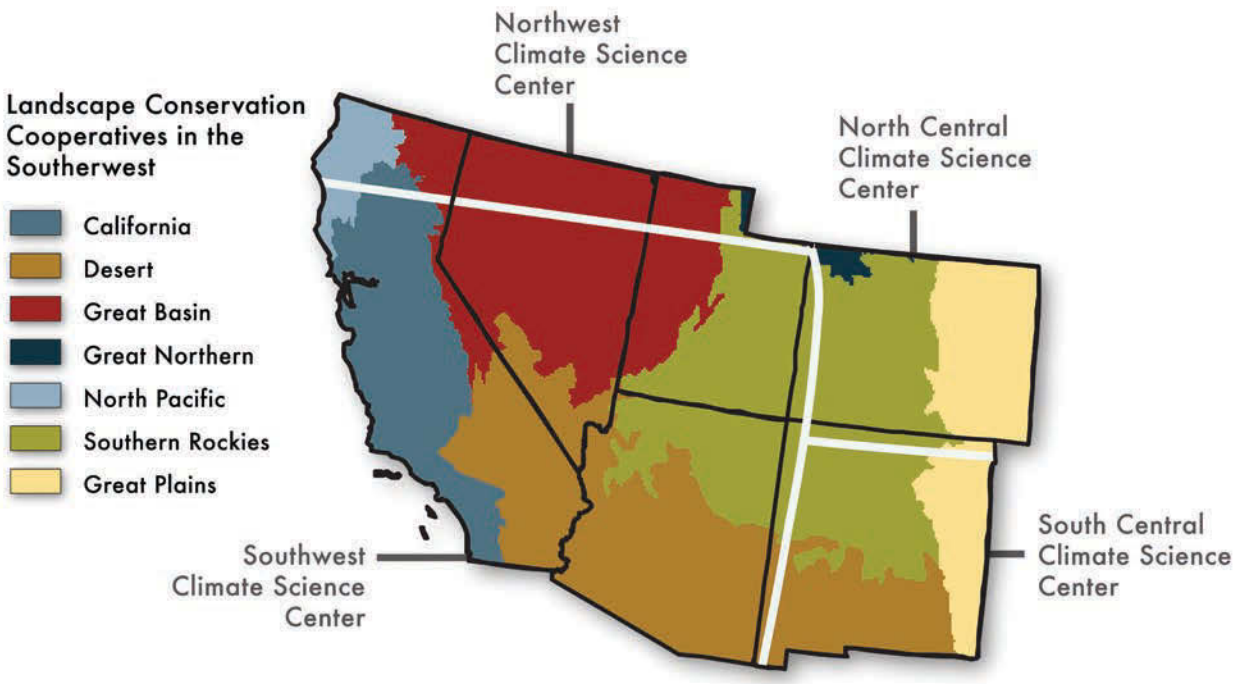

Figure 20.2 Federal climate-science and landscape-management initiatives. Shading indicates Landscape Conservation Cooperatives (http://www.doi.gov/lcc/index.cfm) in the Southwest, overlaid by the approximate research regions of the Department of the Interior's Climate Science Centers (http://www.doi.gov/csc/index.cfm), indicated by the solid white line boundaries.

Table 20.1 Research needs and strategies associated with themes in the *Assessment of Climate Change in the Southwest United States*

Uncertainty theme	Research need	Research strategy
	CLIMATE (CHAPTERS 4–7)	
Distinguishing long-term climate change from interdecadal and interannual climate variability at the regional scale.	Detection and attribution studies, supported by improved observations and data interpolation methods.	Increased emphasis on detection and attribution, supported by rigorous research protocols. Establish and maintain high quality weather and climate stations, prioritizing the largest data voids. Improved representation, in models, of physical processes such as atmospheric convection, evapotranspiration, snowpack formation, and runoff production. Improved models and modeling techniques for multi-year to decade prediction. Increased collaboration between modelers and scientists whose research focuses on observations.
Uncertainty in evaluating trends and variability in mountainous areas and montane environments.	Improved observations across mountain gradients and at a range of elevations.	Increased emphasis on mountain climate analyses, including studies that link climate, hydrology, soil science. Augmented capabilities should address the occurrence of heavy precipitation during winter storms and summer convection, rain versus snow and rain-on-snow events, snowpack formation and melt-off, and basin-scale runoff efficiency. Development of improved techniques for the automated measurement of precipitation in mountainous areas, especially remote locations.
Inadequate confidence in estimates of variations in current and future local climate conditions.	Enhanced meteorology and hydrology observations to better monitor at scales consistent with terrain. Improved modeling for studies of local variability.	Improved climate and hydrological modeling at scales consistent with Southwest terrain.
Assumption that study of past climate variations can provide a representation of future climate that is adequate to estimate future risks.	A suitable replacement for the stationarity principle.	Focused research on non-stationarity. Investigation into statistical approaches for dealing with time-varying climate and hydrological baselines.

Table 20.1 Research needs and strategies associated with themes in the *Assessment of Climate Change in the Southwest United States* (Continued)

Uncertainty theme	Research need	Research strategy
Few scientific studies have considered future projections of climate and hydrologic extremes. Even fewer have focused on regional extremes. Lack of studies increases uncertainty with regard to common claims that the magnitudes and frequencies of some extremes will increase.	Definition of the most impact-based indicators of environmental extremes that are relevant to society. The necessary cross-sector relationships are still in their infancy.	Define extremes by first understanding their impacts in key sectors. Spur and nurture close collaborations between science and the public-private policy sectors, in order to define policy and impact-relevant extremes.
ECOSYSTEMS (CHAPTER 8)		
Despite the clear responses of the distributions of some species to climate, the relationship between changes in climate and recent changes in the geographic distribution of species is highly uncertain. Considerable uncertainty remains on how species and the communities and ecosystems they form will respond to projected changes in climate.	Projections of the effects of climate variability on geographic ranges, accounting for multiple factors affecting species persistence and distribution.	Projections that take into account species' environmental stress tolerances, and ability to adapt. Consideration of environmental change, land-use change, and management interventions. Elucidation of mechanisms of change in the interactions among factors such as climate variation and species fitness. Re-estimation of the probabilities of persistence of species. Knowledge gaps may be partly filled by identification of biotic and abiotic drivers of genetic change and selection, identifying which traits (or combinations of traits) will be targets of this selection, and determining how genetic change and phenotypic plasticity affect selection of potentially correlated traits.
Most projections of current or future distributions of species are based on their current climatic niches, which unrealistically assume that niches are static and uniform.	Species range projections that account for uncertainties due to climate projections that fall outside the ranges of data used to build the models.	Develop robust methods for accounting for changing niche delineations. Characterization of uncertainties associated with extrapolations beyond observations used in constructing niche definitions. Estimating likely temporal and spatial changes in these drivers, given multiple scenarios of climate change.
COASTAL (CHAPTER 9)		
Local jurisdictions vary considerably in their technical expertise and capacity to conduct effective coastal land use management.	Improved understanding of persistent adaptation barriers that inhibit preparedness and active implementation of climate-change adaptation in coastal California.	Social science and communication research aimed at characterizing adaptation barriers. Definition and development of best practices for building capacity for implementation of alternative land-use management practices.

Table 20.1 Research needs and strategies associated with themes in the *Assessment of Climate Change in the Southwest United States* (Continued)

Uncertainty theme	Research need	Research strategy
Extent of ocean acidification and its regional impacts.	Improved understanding of the causes of ocean acidification and its effects on ecosystems and their constituent species.	Monitoring of ocean acidification and diagnostic studies of acidification effects. Analyses to identify sensitive ecosystems, locations, and species.
WATER (CHAPTER 10)		
Twentieth-century water management was based on the principle that the future would look like the past. Statistical downscaling implicitly preserves stationarity in existing large-scale synoptic patterns.	A suitable replacement for the stationarity principle is needed to reduce inhibitions to the process of adaptation and the search for solutions.	Investigation into statistical approaches for dealing with time-varying baselines.
There is a mismatch between the temporal and spatial scales at which climate models produce useful outputs, and the scales of output needed by water decision makers.	Improvements in statistical downscaling methods that currently produce substantially different results. Improved depiction of factors related to fine-scale topography in climate models.	Reconciliation of downscaling methods. Guidance on best practices for interpreting the output of different downscaling methods. Improved model topography and resolution, and validation of output that uses the improved topography in order to address potential mismatches between observed and projected climate variability.
Differing responses across models, especially with respect to precipitation, lack of realistic topography, lack of realistic monsoon simulation, and lack of agreement about ENSO all provide uncertainty, which is difficult to reduce.	Improving models to better simulate modes of climate variability that have important effects on the region, such as ENSO and the North American monsoon.	Conduct intensive modeling studies using models with the best representations of ENSO and North American monsoon dynamics and regional effects. Develop focused initiatives on these key processes.
AGRICULTURE AND RANCHING (CHAPTER 11)		
It is not known how much information private or public intermediaries use to transfer or interpret climate change science and projections and their implications for farmers and ranchers	Investigation of climate change knowledge transfer to farmers and ranchers.	Assess the sector-specific availability and use of information. Evaluate the effectiveness of sector-specific climate change communication and extension strategies, electronic media, and technologies, such as the Internet and phone applications.
ENERGY (CHAPTER 12)		
Climate-change influence on projected peak loads. Estimates exist for California, but not the entire Southwest.	Rigorous projections of peak loads, peak demand, and associated impacts for the entire Southwest region.	Integrated assessment of climate change, demand, peak loads across the region, using common assumptions, model ensembles, socio-economic factors.

Table 20.1 Research needs and strategies associated with themes in the *Assessment of Climate Change in the Southwest United States* (Continued)

Uncertainty theme	Research need	Research strategy
Temporal aspects of future power production.	Simultaneous spatial and temporal assessment of evolution of power production, plant performance, fuel type and mix.	Estimate temperature impacts on different types of electricity-generating capacity and power-plant performance throughout the Southwest. Improve projections of spatial shifts in wind regimes; investigate probability and duration of no-wind conditions on hot days. Improve projections of extreme surface temperatures and their effects on photo-voltaic and concentrated solar power production. Estimate evolution of current and future power, with respect to fuel type.
Vulnerability of power plants to flooding.	Flood risk is site-specific, and relatively few studies directly quantify potential climate change impacts on hydropower production.	Conduct site-specific studies of power plant vulnerability to flooding. Synthesize and assess individual studies, in order to evaluate vulnerability and risk for the region.
Exposure and vulnerability of thermoelectric power production to drought and climate change.	Rigorous assessment of the exposure and vulnerability of thermoelectric power production to drought and climate change.	Assessment of hydrologic conditions, combined with operational characteristics and institutional factors. Development of a definitive measure of aggregate impact. Inventory and rigorously assess the robustness of existing contingency plans for individual plants.
A lack of accurate projections of future ground-level solar radiation adds to uncertainty in regional energy potential and production projections.	Improved simulation of regional cloud cover, directly from physical principles.	Increase spatial resolution in climate models, and improve model physics for estimation of ground-level solar radiation. In the meantime, ground-level radiation generated by global and regional climate models should be interpreted cautiously.
Uncertainty in future transportation sector fuel types and use.	Examinations of the type and intensity of future fuel use in the transportation sector.	Projections of the type and intensity of fuels used in the transportation sector, given projected future climate changes.
Implications of climate change across the entire Western interconnection.	Comprehensive assessment of impacts of climate change on multiple modes of power production, in conjunction with projections of shifts in power demand, and risks to the transmission grid.	Evaluate concurrent impacts of climate on West-wide hydropower production, coincident impacts on thermoelectric production and induced shifts in electric power demand. Include studies of fire risk to the transmission grid, given projected increases in regional fire frequency. Identify loss minimizing operation practices.

Table 20.1 Research needs and strategies associated with themes in the *Assessment of Climate Change in the Southwest United States* (Continued)

Uncertainty theme	Research need	Research strategy
	URBAN AREAS (CHAPTER 13)	
Determination of the adaptive capacity of urban communities.	Integrated evaluation of urban adaptive capacity and institutional complexity.	Evaluation of the connections between municipal agency funding and how municipal services capabilities might be used to implement mitigation and adaptation strategies. Studies of the fiscal capacity of localities in relation to their ability to monitor and act on climate change challenges.
Urban area observation collection, data amount, availability, and format are not sufficiently standardized to fully assess the ways in which cities may contribute to climate change through their urban metabolisms, such as flows of water, energy, materials, nutrients, and air.	Inventory and evaluation of data collection and analysis practices.	Urban metabolism studies can improve understanding of a host of climate-change vulnerabilities such as water use and waste generation. Improve collection of information on urban vegetation cover, to evaluate urban water consumption patterns in the Southwest. Improve quantification of the contribution of urban areas to climate change for sectors other than transportation. Couple household-level energy use with land-use data, to reveal important aspects of urban activities and mechanisms. The expected increase in climate-driven urban-fringe fires will call for improved post-fire monitoring, management, and treatment of stormwater runoff to reduce impacts to city water supplies and downstream ecosystems.
There is a paucity of observations on land and built-environment interactions with the atmosphere in the Southwest's urban centers.	Better information is needed on building technologies, particularly impermeable surfaces and surface albedo (the portion of solar energy reflected back from a surface to the atmosphere).	Improved use of information on urban vegetation cover to evaluate albedo patterns in the Southwest.
	TRANSPORTATION (CHAPTER 14)	
The magnitude of potential impacts to the transportation system for a particular system or location is too uncertain to be reliably estimated. Depending on the levels and types of investments now, the effects of climate change could be significantly increased or reduced.	Studies of the impact of climate change on passenger travel. Quantification of key variables for evaluating economic impacts of changing climate.	Focus studies on key economic variables, such as loss of time, loss of money, loss of productivity (and wages), relocation costs, and loss of life. Prioritize future research to quantify long-term effects of climate change on transportation systems. Refine studies to simultaneously examine multiple scenarios of climate changes of various magnitudes in conjunction with multiple scenarios of levels and types of investments and the effect of multiple timelines for implementation of investments.

Table 20.1 Research needs and strategies associated with themes in the *Assessment of Climate Change in the Southwest United States* (Continued)

Uncertainty theme	Research need	Research strategy
	PUBLIC HEALTH (CHAPTER 15)	
Limited understanding of the associations between meteorological factors and health impacts contributes to uncertainty, and limits the capacity of current statistical models to predict future health impacts.	High-quality, high-resolution long-term health and climate data are necessary to fully characterize their relationship and adequately estimate future impacts to health from climate change. Deficiencies in the quality of health data limit our ability to characterize linkages between climate change and health and develop predictive models for climate-related health impacts.	Incorporate physiological, societal, and behavioral effects to reduce uncertainty in predicting health outcomes. Improved data collection, combined with exploratory analyses that make use of sparse data, and hypothesis-driven diagnostic analyses can help build experimental predictive capacity.
Uncertainty in the future occurrence of allergies and asthma, in association with future pollen production, which may be influenced by increases in atmospheric CO_2 concentration.	Examination of linkages between pollen production, phenology, and public health.	Systematic focus on allergies and asthma, in conjunction with field observations, greenhouse experiments, and modeling. Develop interdisciplinary research initiatives and multidisciplinary research teams.
Uncertainty due to possible multiple causes of mortality in the case of heat-related deaths.	Criteria for heat-related mortality are not standardized. It is often difficult to identify where and when cases were exposed to infectious diseases.	Carefully explore questions of exposure source and location at the time of diagnosis, to identify factors other than temperature (e.g., socio-economic or other environmental issues) that influence the relationship of climate change and mortality.
Limitations to public health data.	Data on the spatial attributes of vector-borne diseases are required to estimate future infectious disease impacts. Criteria for identifying cases are not always consistent, suggesting a need to standardize diagnostic criteria. Multi-year data sets with high spatial and temporal resolution from multiple locations are needed to allow us to assess risk changes over time and estimate future impacts at a regional scale.	Develop standards for diagnostic criteria associated with vector-borne diseases. Invest in consistent, long-term monitoring networks, with sufficient resolution to answer research and public health professionals' needs.

Table 20.1 Research needs and strategies associated with themes in the *Assessment of Climate Change in the Southwest United States* (Continued)

Uncertainty theme	Research need	Research strategy
Insufficient understanding of the physiological, societal, and behavioral factors that affect human health, and the interactions between these factors.	Predictive modeling of climate impacts on health that accounts for the complexity introduced by non-climatic factors.	Assess the linkages between climate and human health at city, state, and regional levels, and develop action plans for each level that reflect differences in current and predicted climate conditions and vulnerabilities. Characterize vulnerability and future risk not only in terms of the impacts of climate change on health, but also with attention to demographics, local geographical differences, and socioeconomic factors.
TRIBAL COMMUNITIES (CHAPTER 17)		
Lack of scientific studies that have examined climate-change impacts on Native lands within the Southwest region. Lack of data and observations is a substantial source of uncertainty in documenting changes and attributing observed changes to anthropogenic climate change.	Indian reservations need improved monitoring of climatic conditions to provide tribal decision makers the necessary data to quantify and evaluate the changes taking place for planning and management of their resources. Reservations lack the data necessary for accurate downscaling of climate models, because meteorological monitoring is sparse over areas of significant size. Additional studies are needed, in order to make comprehensive assessments of observed changes.	In addition to commonly used land-based observations, a research program to evaluate climate change impacts on Native lands in the Southwest might include: increased use of remotely sensed observations to detect environmental changes, ethnographic studies of traditional environmental knowledge, and citizen-science observations. An inventory of climate-related observed changes could provide the first step in developing a comprehensive assessment.

20.4 Research Strategies from Southwestern Ecoregional Initiatives

Each of the Landscape Conservation Cooperatives[iv] (LCCs, Figure 20.2) is conducting strategic syntheses of common resource management priorities and related science needs across the Southwest. Although LCCs are not exclusively directed toward research nor toward climate adaptation and mitigation, climate change information needs are a major part of the LCCs' agenda to work at a landscape scale to protect natural and cultural resources. We queried four LCCs that cover the majority of the Southwest assessment area—California, the Desert region, the Southern Rockies, and the Great Basin[v]—regarding the status of their syntheses, as well as for information on the primary sources used to develop these syntheses. Responses indicated that the LCCs are in the earliest stages of conducting comprehensive science-needs assessments. They anticipate they will be able to make available in the near future a full compilation of these sources, the criteria

for developing priorities among science needs, and approaches for applying the criteria. These assessments will be of immense value in the structuring of climate change-related research in the Southwest.

Additionally, a number of federal, state, and local agencies, universities, and inter-organizational cooperatives in the Southwest have started to consider research needs pertaining to climate adaptation to help them achieve their missions. Federal and state agencies, along with their university partners, have conducted several workshops over the past four years to acquaint land and water management agency leadership and staff with the state of climate-change research in the Southwest, and to provide opportunities for participants to articulate what they consider important uncertainties and gaps in our scientific understanding. Table 20.2 lists a sample of recent workshops held on climate-effects science in the Southwest. Incorporating information from such efforts in climate-change-related research needs assessments will be important in creating climate-effects-oriented research programs that are effectively integrated with land and water managers.

20.5 Strategies to Improve Characterization in Climate and Hydrology

Given the Southwest's aridity and climatological variability, water resources managers in the region face many challenges in predicting when they will have too much or too little water. Water resource managers have issued several "requirements" surveys of their water users' perceived needs, including data, methods, tools, and agency capacity. Many of these surveys were developed to address implications of a changing climate for water resources (Milly et al. 2008; Karl et al. 2009) and concerns about how water managers can adequately plan for and manage such changes (Brekke et al. 2009). Whether they are focused on preparing for longer-term climate change or shorter-term weather and climate variations, a common theme among these surveys is the promotion of research and capacity-building that leads to:

- better-quality predictions;
- better use of existing predictions while we wait for quality to increase; and
- better communication of risk and uncertainty during decision-support processes.

Requirements surveys tend to be better barometers of the relevance of research and development efforts than of research feasibility. The following are some requirements surveys that have been completed in recent years, all of which offer insight on user needs related to water-cycle science and prediction research:

- "Addressing Climate Change in Long-Term Water Resources Planning and Management" (Brekke et al. 2011) outlines the various types of analyses necessary to assess climate-change implications for water-resources management. It offers a technical discussion of desired capabilities, current capabilities, and gaps, and is aimed at science/management research collaborations.
- "Water Needs and Strategies for a Sustainable Future" (WGA 2006) offers states' perspectives regarding needs related to several water management aspects,

Table 20.2 Recent workshops that have included discussion about strategies for climate-effects science in the Southwest

Workshop Title	Sponsors	Publication of results
Natural Resource Mitigation, Adaptation and Research Needs Related to Climate Change in the Great Basin and Mojave Desert	Fish and Wildlife Service, US Geological Survey, National Park Service, Desert Research Institute, Bureau of Land Management, Environmental Protection Agency, University of Nevada Las Vegas	Hughson et al. 2011
Effects of Climate Change on Fish, Wildlife and Habitats in the Arid and Semiarid Southwestern United States: Putting Knowledge and Science into Action	Fish and Wildlife Service, US Geological Survey, Climate Assessment for the Southwest	Guido, Ferguson and Garfin 2009
Climate Change, Natural Resources, and Coastal Management: a Workshop on the Coastal Ecosystems of California, Oregon, and Washington	Fish and Wildlife Service, US Geological Survey	USFWS 2009
The Climate and Deserts Workshop: Adaptive Management of Desert Ecosystems in a Changing Climate	Desert Managers Group, George Wright Soc, University of California, University of Arizona, University of Nevada, Great Basin Cooperative Ecosystem Studies Unit, The Wildlife Society, Climate Assessment for the Southwest, The Nature Conservancy, Bureau of Land Management	Desert Managers Group 2008
Research and Development Workshop: Roadmap – Managing Western Water as Climate Changes	Bureau of Reclamation, National Oceanic and Atmospheric Administration, US Geological Survey	Brekke et al. 2009
Southwest Climate Summit	US Geological Survey, Climate Assessment for the Southwest (CLIMAS)	Southwest Climate Science Center 2012

inviting both research and capacity-building activities. The report emphasizes the need for both enhanced hydrologic data collection to track changing climatic conditions and improved capabilities in the areas of hydrologic prediction, modeling, and impact assessment. An associated "Next Steps" report was subsequently issued (WGA 2008), offering a more technical discussion of needs, including those related to managing during drought and other shorter-term weather variations and developing locally relevant (downscaled) long-range projections of climate and hydrology needed to support climate-change vulnerability and adaptation assessments in the Western United States.

- "Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change" (Barsugli et al. 2009) discusses water utilities' perspectives on global and regional climate projections in relation to their planning activities. It reviews the state of science on developing global to regional climate projections and prospects for improving this science.
- "Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning" (Means et al. 2010) serves as a companion to Barsugli and others (2009), providing a review of methods for making decisions under climate-change uncertainty, discussing research needs in relation to probabilistic information on data and modeling uncertainties.
- "The Future of Research on Climate Change Impacts on Water—A Workshop Focusing on Adaptation Strategies and Information Needs—Subject Area: Water Resources and Environmental Sustainability" (Raucher 2011) focuses on needs and potential research directions in five areas, including flooding and wet weather, water supply and drought, and the water-energy nexus.

Next-generation climate models should be evaluated for their credibility in making climate projections useful in environmental risk assessments (e.g., Brekke et al. 2008), as must assessments of Southwestern ecosystems involving hydroclimatological drivers. As an initial step in this assessment, the Southwest Climate Science Center[vi] is evaluating the characteristics of California coastal zone influences, the sharp topographic gradients characteristic of the mountainous Southwest, and the North American monsoon.

Although their occurrence is highly variable, intense storms associated with narrow currents of concentrated water vapor ("atmospheric rivers" or ARs) make landfall on the California coast. ARs often make the difference between floods and plentiful water supply versus drought, and are therefore important to planning for integrated water resources and flood planning (see Chapter 4). ARs have been shown to penetrate into the interior Southwest, so the influence of climate change on their frequency and magnitude is in need of additional attention (Dettinger et al. 2011).

There is considerable uncertainty about how the Southwest's major river systems will evolve in the future. For example, in the Sacramento-San Joaquin drainages and San Francisco Bay, differences in projected futures arise from the different sensitivities of global climate models to the range of greenhouse gas emission trajectories. Such uncertainties propagate further into other drivers of transformative change such as landscape modification, water development, and pollutant loads (Cloern et al. 2011).

20.6 Strategies to Improve Characterization of Impacts and Vulnerabilities

Widespread drought has affected large areas of the Southwest for the last decade (see Chapter 5). Concern about persistence of this drought—and of longer, more severe droughts—due to projections for continued variability in precipitation amounts, decreased streamflows, and increased temperatures (see Chapters 6 and 7), is generating new research approaches that will improve policy prescriptions for wildland and urban/suburban systems (MacDonald 2010). However, the availability of scientific information

regarding climate change and the capacity to adapt to or mitigate it are uneven across the Southwest. California is a leader among states in assessing climate change impacts associated with natural and managed systems, having completed its second integrated assessment, including thirty-nine individual studies (Franco et al. 2011). Other Southwestern states have not implemented programs to conduct assessments at this depth or breadth.

In addition, the importance of traditional knowledge of indigenous communities is beginning to be acknowledged in ecosystem management (see, for example, the Traditional Knowledge Bulletin[vii] of United Nations University). In other work, interviews with seventy Navajo elders were used to catalog changes in weather, vegetation, location of water sources, and the frequency of wind and dust storms, helping to corroborate research on sand dune movement and growth (Redsteer, Bogle and Vogel 2011). Inclusion of traditional knowledge from the roughly 180 Southwestern tribes could improve both climatic analyses and climate adaptation. Native Americans in the Southwest are thought to be particularly vulnerable to climate change (see Chapter 17). Resiliency can be affected by multiple climate-related threats, and because of tribal communities' close reliance on reservation resources for sustenance, economic development, and the maintenance of cultural traditions, they are particularly vulnerable (National Wildlife Federation 2011). Further assessment of such threats to Native American communities appears to be a pressing need across Southwestern landscapes.

Projections of the potential impacts of coastal flooding in California due to sea-level rise are presently imperfect due to information needs in a number of areas (see Chapter 9). Among these are (1) the capability to model factors such as flood duration and velocity; (2) economic analysis of transportation risk, health issues, and habitat loss; (3) integration of coastal development scenarios; and (4) better characterizations of coastal zone policies (Hebeger et al. 2011).

Climate-driven changes in stream temperature and hydrology are affecting aquatic ecosystems and fishes throughout the West (see Chapter 8), reinforcing the need to synthesize trends in monitoring data, form cross-disciplinary collaborations, and develop alternatives for climate adaptation across river basins (Rieman and Isaak 2010).

Few environmental studies covering the Southwest have explicitly considered dust flux and wind erosion, yet these factors are important drivers of ecosystem processes, can cause human health impacts, and act as a source of uncertainty in climate models (Field et al. 2010). Additional information could help determine ways to reduce the dust layer derived from human activities that is accumulating in the Colorado River Basin snowpack. Dust has increasingly reduced the capacity of the snow to reflect solar radiation, hastening and increasing snowmelt and causing early runoff in this important source of Southwestern water supply (Painter et al. 2010) (see Chapter 4, Box 4.1).

Climate significantly impacts ecosystem structure and plant-animal interactions, such as in plant and bird communities in montane Arizona, where Martin and Maron (2012) demonstrated that declining snowfall indirectly affects both plant and bird populations by allowing more extensive grazing by elk. It is becoming increasingly important for managers to consider such interactions as they struggle to achieve natural resource goals in a changing environment.

As in other regions, keystone species may be affected by climate change and this may have consequences for entire ecosystems. One such Southwestern icon, *Yucca brevifolia*,

lends its name to Joshua Tree National Park. A study of past and future shifts in its distribution indicates that only a few of its populations appear to be sustainable, while barriers to dispersal may limit its potential to expand its range (Cole et al. 2011). This is but one example of how climate and land use change will affect species' capacity to migrate. Additionally, since the pace of shifting climate is itself variable, climate changes can affect biodiversity and species that are found only in the Southwest (endemic species); thus, species in many marine and terrestrial environments in the Southwest are likely to be affected (Burrows et al. 2011; Sandei et al. 2011). However, phenotypic plasticity and evolutionary potential could provide a degree of resilience and enhance probabilities of persistence for populations and species in the face of a changing climate (Reed et al. 2011). These findings point to the need for new approaches to integrate climate variability in population biology research in the Southwest.

As a consequence of such climate-species interactions, the nature of geographic boundaries for Southwestern deserts likely will change due to a number of factors affecting vegetation composition, diversity and productivity, water availability and evapotranspiration, and soil erosion (Archer and Predick 2008; Gonzales 2011; Munson et al. 2012). Southwestern forests and woodlands that are sensitive to fire and insect infestations appear to be increasingly vulnerable to rapid conversion to novel vegetation types (Williams et al. 2010). Climate is a principal driver for wildfire frequency, intensity, type, extent, and seasonality, and fire regimes in the Southwest are affected by the invasion of non-native species such as *Bromus tectorum* (cheatgrass) in the Mojave Desert (Brooks et al. 2004). Increases in wildfire related to climate change are projected for future decades due to changes in ignitions, fuel condition, and volume; a new generation of dynamic vegetation models appears necessary to help assess fire severity (Hessl 2011).

A growing awareness of the effects of ongoing and impending climate change on Southwestern ecosystems, urban areas, and socio-economic structures is creating a need to review management approaches to evaluate what lines of research are needed to fill information gaps. As new climate-driven natural and human community structures and relationships develop, it will be important for research strategies relating to climate effects to be tailored to address not only scientific uncertainty, but also to address our need to manage adaptively.

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Endnotes

i See http://greatbasin.wr.usgs.gov/GBRMP/

ii Western Water Assessment, personal communications.

iii See http://www.doi.gov/csc/southwest/

iv See http://www.doi.gov/lcc/

v See http://californialcc.org/, http://www.usbr.gov/WaterSMART/lcc, and http://www.blm.gov/id/st/en/prog/Great_Basin_LCC.html

vi See http://www.doi.gov/csc/southwest/

vii See http://tkbulletin.wordpress.com/