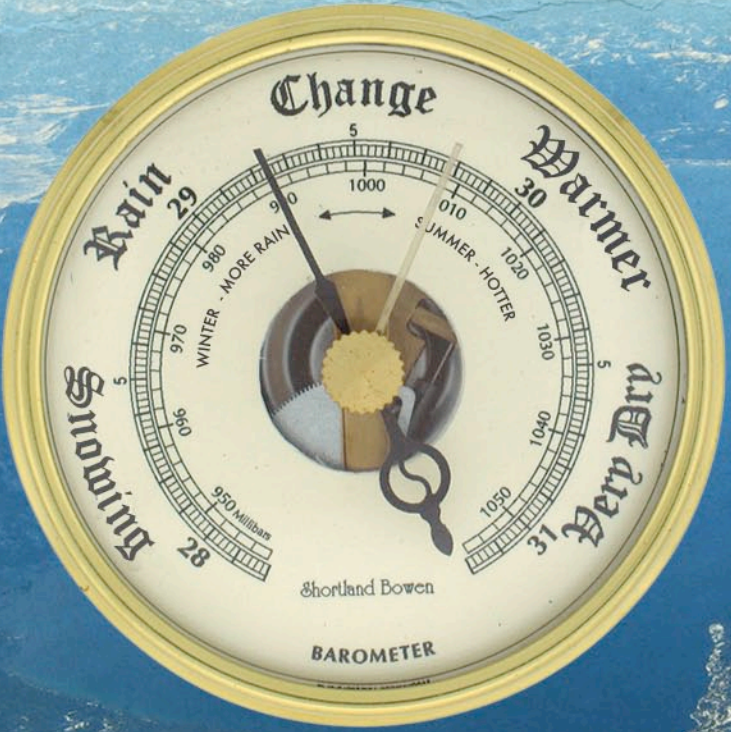
LAKE TAHOE CLIMATE CHANGE SCIENCE SYNTHESIS

AQUATIC RESOURCES

FINAL NOVEMBER 2010



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Lake Tahoe Climate Change Science Synthesis – Aquatic Resources

Final Report – November 2010

This document synthesizes existing scientific information related to climate drivers and aquatic resources as of 2010 to inform climate change planning and resource management decisions in the Tahoe Basin. It is one portion of a project that provides a set of climate change adaptation tools for the Lake Tahoe aquatic resource managers. This synthesis, as well as the other tools developed using US Army Corps funding, provides a preliminary structure and process that allows Lake Tahoe resource managers to document and explore the potential impacts and responses for other Lake Tahoe systems in the future. This product would not be possible without the generous participation of several Tahoe Basin regulatory and project implementing entities.

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EXECUTIVE SUMMARY

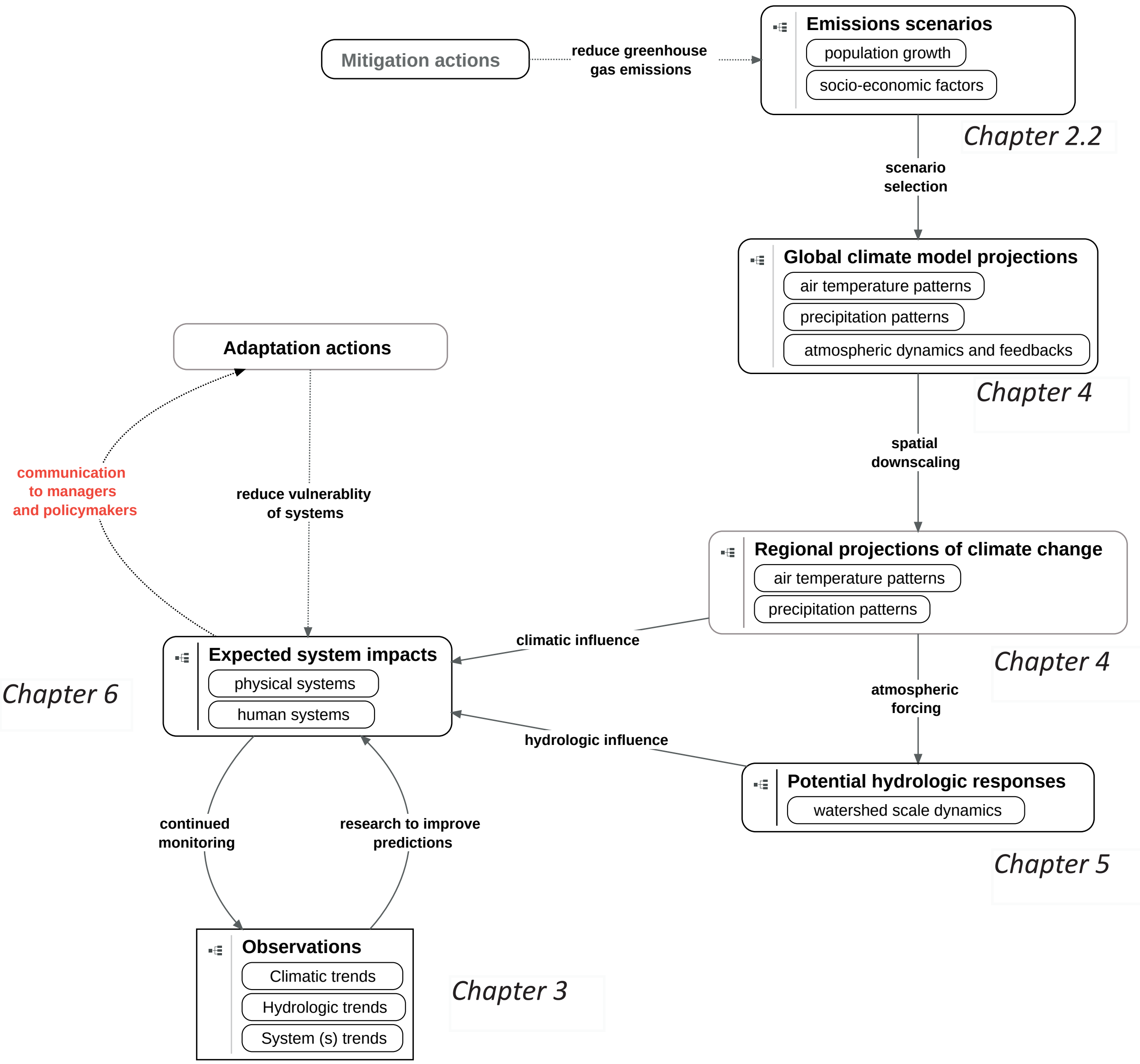
This document synthesizes existing scientific information related to climate drivers and aquatic resources to inform climate change planning and resource management decisions in the Lake Tahoe Basin. This synthesis aims to make global climate change science information accessible and relevant to Lake Tahoe Basin resource managers to inform decision making that will improve the resiliency of the Lake Tahoe physical and human systems to climate change. It also aims to improve policy and decision makers' understanding of the vulnerability of Lake Tahoe systems to climate change, including the level of uncertainty contained in future climate projections and anticipated impacts. The document has been thoroughly reviewed by scientists with expertise in the systems climate change impacts on natural systems to ensure accuracy of its content. Timely and regular communication of science related to anticipated climate change impacts will help decision makers identify the best options for protecting Lake Tahoe systems into the future.

Scientists use models to predict future climatic trends. Figure ES.1 summarizes the linkage between the science of climate change and the role mitigation and adaptation actions may play. A range of emissions scenarios are used to estimate future amounts of greenhouse gases in the atmosphere and serve as inputs to global climate models (see Chapter 2.2). Temperature and precipitation change projections for the Lake Tahoe Basin are produced by downscaling global climate models (see Chapter 4). Changes in temperature and precipitation result in hydrologic responses (see Chapter 5), which in turn are expected to impact the physical and human systems in the Lake Tahoe Basin (see Chapter 6). The identification of adaptation actions can reduce the vulnerability of physical and human systems to future climate change (see Chapter 7). The majority of this synthesis focuses upon the aquatic resources within the physical and human systems with one exception, forests, due to the inherent physical interconnection of forests to Lake Tahoe aquatic resources.

There is high confidence that reductions in the future rate of greenhouse gas (GHG) emissions will be important for reducing future climate change as well as the potential negative system impacts. However, the greater number of assumptions and complexity of a system and its relationship to climatic conditions, the more difficult it is to predict future outcomes with a high level of certainty. The pathway leading from global greenhouse gas emissions to atmospheric composition changes, climate changes, and finally to system-level impacts in the Lake Tahoe Basin is indeed complex, and requires a multitude of important simplifying assumptions to model such a chain of cause and effects. The cumulative uncertainty resulting from assumptions employed at each step of the process should be considered when using results for decision making. The content of this synthesis represents the current understanding, which is rapidly evolving. A confidence ranking scale has been defined to simply communicate confidence in a number of different conclusions throughout this document (Table ES.1).

Confidence ranking	Description
High	General scientific agreement of conclusion that is supported by a number of monitoring data, modeling results, research or best available scientific information.
Moderate	Scientifically supported but consensus or agreement is not present due to lack of information, moderate differences between studies, or limitations for drawing general conclusions from limited scientific information.
Low	Lack of information or directly conflicting results between studies, opinions and/or research findings.

Table ES.1. Ranking scale used to provide simple communication of general confidence of a number of different conclusions presented throughout this science synthesis.



A diagram summarizing the linkages between global climate change projections, potential system impacts, and management and policy actions implemented to reduce system vulnerability to climate changes and/or reduce future greenhouse gas emissions. The purpose of this science synthesis is to communicate the existing science of potential Lake Tahoe impacts of global climate change to managers and policy makers. The relevant chapters of the science synthesis are noted.

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CLIMATE CHANGE LINKAGE SUMMARY DIAGRAM

FIGURE ES.1

CLIMATE CHANGE MODELING

Although there is substantial uncertainty associated with climate change predictions, there is strong scientific consensus that GHG concentrations will continue to increase, which will alter global climate patterns. Similarly, there is a general consensus by scientists that reductions in greenhouse gas emissions can reduce the magnitude of future climate change. Climate science and associated models have historically been focused on large spatial scales, but now are being challenged to predict climatic patterns at regional scales. There are numerous widely-accepted global climate models, each with variations in the representation of the physical and chemical processes and interactions that drive climate patterns. Therefore, climate scientists often use multiple models to evaluate potential future climate patterns and trends, since there is a large amount of uncertainty in our ability to model complex and dynamic systems.

All projections of future climate and hydrology by global climate models are very sensitive to future carbon and/or greenhouse gas emissions scenarios. Emissions scenarios are plausible descriptions, without likelihoods, of the future states of the world and are used to estimate future greenhouse gas emissions. They vary based on assumptions about the nature of population growth and economic development in the future and the resultant estimated rates of fossil fuel and greenhouse gas (GHG) emissions. The two most commonly used emissions scenarios are the A2 and B1 scenarios, which provide a reasonable range of potential future emissions. A2 assumes a continued exponential increase in GHG emissions over the next 100-yrs, with some reduction relative to current rates. B1 assumes a significant global reduction in GHG emissions from industrialized and developing nations with the peak in global carbon emission reached in the middle of 21st century and then declining back to carbon emission rates of the 1970s (see Figure 2.8).

OBSERVED CLIMATE CHANGES IN LAKE TAHOE

Measurable atmospheric, hydrologic and aquatic ecosystem changes have been observed over the past 4 to 5 decades in the Lake Tahoe Basin and are likely be exacerbated in the future given current regional climate projections. A number of existing analyses of past records for California, the Sierra Nevada and Lake Tahoe provide evidence for observed recent climatic, hydrologic and system trends (see Chapter 3). Historic trend analysis indicates Lake Tahoe regional average summer and winter temperatures have increased, the average annual snowpack has declined and the spring snowmelt occurs on average 2 weeks earlier than it did in the 1960s. An increasing trend in the annual minimum surface water temperatures of Lake Tahoe has also been detected from existing Lake Tahoe data. It must be noted that large inter-annual variability does exist and long-term datasets are necessary to increase our confidence in the actual change of climate and system responses into the future. Understanding of this variability should be incorporated into the process of using climate model projections to assess and prioritize risk in the future.

CLIMATE CHANGE PROJECTIONS FOR LAKE TAHOE

There is consistent agreement that air temperatures in California and the Lake Tahoe Basin will continue to increase, but the magnitude is strongly dependent upon the emissions scenario and global climate model used. Generally, research provides mixed results on the future of California and Lake Tahoe Basin annual precipitation totals. Continued reduction in winter snow totals with a concurrent increase in winter rains is predicted across the Sierra Nevada region and in the Lake Tahoe Basin. Some models predict increases in total precipitation in Northern California and drier conditions in Southern California. Other models predict no discernible change in the total Northern California precipitation by 2100.

Chapter 4 presents a variety of specific climate research projections that provide quantitative estimates of annual temperature and precipitation patterns into the next century. The absolute structure of the 100-yr time series predictions and the estimated magnitude of change by 2100 vary significantly with different global climate models and emissions scenarios. Thus, multiple model and emissions scenarios are used to bracket the range of plausible projected climate conditions. Table ES.2 provides a summary of the potential climatic trends that may occur over the next century within California and Lake Tahoe based on the existing local, regional and global climate science available.

Climate variable	Spatial context	Direction of expected change	Seasonal patterns	Confidence of change and seasonal patterns
Average air temperatures	Lake Tahoe Basin	Increase	Increase in annual average maximum temperatures (summer); Increase in annual average minimum temperatures (winter); Increase in average annual temperatures	High
Extreme temperature events	California	Increase	More frequent heat waves and hot days (summer); Less frequent freezing spells (winter)	High
Precipitation totals	California	Slight decrease	Increase in winter; Decrease in summer and spring; Less frequent precipitation events	Low
Extreme precipitation events	California	Increase	Increase in frequency of high precipitation events in winter	Moderate
% of precipitation as snow	Lake Tahoe Basin	Decrease	Increase in winter air temperatures will increase likelihood of more precipitation falling as rain	Moderate
Rain on snow events	Lake Tahoe Basin	Increase risk	Increase in winter air temperatures will increase likelihood of more frequent rain on snow events	Low

Table ES.2. Lake Tahoe Basin climate change summary.

POTENTIAL HYDROLOGIC RESPONSES

Expected hydrologic impacts of climate change in Lake Tahoe include a reduced winter snowpack, a trend toward earlier spring snowmelt timing and an increased likelihood of rain on snow events, which have produced a number of the largest floods on record in the Lake Tahoe Basin.

A number of different hydrologic models have been used to predict statewide, regional, and Lake Tahoe Basin specific (e.g., Lake Tahoe Watershed Model, the Lake Clarity Model, the Pollutant Load Reduction Model (PLRM), etc.) hydrologic responses to future climatic conditions. Table ES.3 provides a summary of the general projected changes in watershed hydrology relevant to Lake Tahoe. The confidence of the changes is not provided due to the difficulty of simultaneously evaluating confidence of emission scenarios, climate model results and hydrologic model outputs. Although both future climatic and hydrologic conditions are uncertain and the inter-annual variability of hydrologic parameters is significant, it is reasonable to consider the potential century-scale hydrologic projections when developing local adaptation strategies.

Hydrologic Variable	Spatial Context	General Change	Primary Climatic Drivers
Floods	Lake Tahoe (Upper Truckee River)	Increased risk and magnitude	Increased likelihood of rain on snow events; Winter precipitation event magnitude increases
Winter soil moisture	Lake Tahoe	Increase	Winter precipitation volume increases
Droughts	Lake Tahoe	Increased risk and severity	Increased summer temperatures result in reduced snow accumulation and earlier snowmelt
Winter streamflow volume	Sierra Nevada Region (American River)	Increase	Winter temperature increases % of precipitation as snow
Spring/Summer streamflow volume	Sierra Nevada (American River)	Reduction	Increased temperatures result in reduced snow accumulation and earlier snowmelt
Summer soil moisture	Northern Sierra Nevada	Reduction	Increased temperatures result in reduced snow accumulation and earlier snowmelt
Snow accumulation	Sierra Nevada Region	Reduction	Spring and summer temperature increases
Streamflow timing	Sierra Nevada Region	Earlier in year	% of precipitation as snow; Spring/Summer temperature increase

Table ES.3. Summary of projected of hydrologic response trends in California and Lake Tahoe over the next century.

EXPECTED LAKE TAHOE SYSTEM IMPACTS

Given existing projections of climatic and hydrologic future conditions, a number of potential impacts to Lake Tahoe systems relevant to aquatic resources have been identified based on existing state, regional and local climate related research (Table ES.4).

System	Expected Impacts
PHYSICAL SYSTEMS	
Forests	• Increased risk of wildfire frequency, extent, and intensity • Shift in the distribution and range of forest flora and fauna • Increased tree mortality rates • Reduced forest biodiversity
Riparian (SEZ)	• Changes in soil moisture dynamics • Increased erosion risk • Increased stress on cold water fish species • Reduced riparian (SEZ) biodiversity
Built environment	• Increased risk of flooding
Lake Tahoe	• Reduced frequency of lake water column turnover • Increased risk of low dissolved oxygen in deep water column • Reduced lake biodiversity
HUMAN SYSTEMS	
Water supply	• Increased risk of water use conflicts

Table ES.4. Expected impacts from climate change by Lake Tahoe system.

Detecting a real change in highly variable systems often requires long data records, usually extending for many years or decades, and the length of the records improves our ability and confidence to detect the signal of a system change beyond natural variability. The occurrence and extent of impacts will depend on magnitude and timing of climate changes and a number of other environmental factors. Predictions of climate change impacts on physical and human systems often involve using the outputs from one type of model to drive another type of model or set of sub-models. The cumulative uncertainties associated with the use of layers of models make it extremely difficult to rigorously test hypotheses about changes to natural systems related to climate change. However, our current understanding of how natural and human systems function and interact can allow reasonable general projections of possible shifts in system conditions relative to current and historic states.

FORESTS AND RIPARIAN (SEZ)

Climate changes and associated impacts are likely to result in a number of complex changes to Lake Tahoe systems. Greater seasonal fluctuations in moisture availability and increased frequency of wildfires may create conditions that are likely to substantially alter the composition and function of forest ecosystems. Seasonal soil moisture patterns are expected to change, with a relative increase in winter soil moisture and decrease in summer soil moisture from historic trends. These seasonal soil moisture shifts would have significant impacts on forest and riparian (SEZ) vegetation communities. Biodiversity is a measure of the health of an ecosystem, and a higher level of biodiversity indicates a greater number of functional habitats and niches available for a wide range of species to occupy and survive. For the purposes of this scientific synthesis the impact “reduced biodiversity” is used to simplify the communication of ecosystem impacts and is assumed to encompass a multitude of the interactions and ecosystem community dynamics that result from the loss of habitat, loss of sensitive species or increase in less desirable species better adapted to future climate. Tree mortality rates may increase in forests and a reduction in biodiversity may occur in all alpine and subalpine forests and aquatic systems.

BUILT ENVIRONMENT

Climate change impacts include an increased risk of extreme events such as flooding, landslides, and wildfires, which are typically of much greater concern when a feature of the built environment is threatened. Climate changes may exacerbate the challenges of stormwater management due to projected increases in frequency and intensity of peak flow runoff. However, PLRM simulations provided by Coats et al. (2010) provide very compelling evidence that the implementation of identified pollutant reduction opportunities in the urban areas within Lake Tahoe Basin will far exceed the potential increased water quality risk from urban areas as a result of global climate change.

Long-term predictions for the Lake Tahoe Basin call for little change in total annual precipitation amounts; however, the percentages of rain and snow that make up that total is predicted to shift towards greater amounts of rain and less snow. Hydrologic analyses completed for public infrastructure and stormwater improvement projects currently utilize historic datasets and/or simple hydrologic regression equations to estimate infrastructure routing and capacity needs. Reliance on historic data to estimate hydrologic conditions for Lake Tahoe may not be representative of future conditions in 20 to 30 years (Milly et al., 2008). While hydrologic projections driven by climate models contain substantial uncertainty, which has yet to be quantified, they are presently among the most useful tools available for understanding potential changes in hydrologic conditions that may need to be considered in the future. As the potential impacts of climate change are better understood, the fields of engineering, construction, management, and regulation will need to address these issues globally. It is crucial that Lake Tahoe stay abreast to the state of the art practices for estimating future hydrology given climate change considerations.

The use of deterministic future hydrologic predictions to inform current planning and design of infrastructure should be done only with an understanding of the uncertainty and assumptions associated with such predictions.

LAKE TAHOE

The UC Davis Tahoe Environmental Research Center (TERC) recently completed a study to project the impacts that climate change will have on the lake. This study, which used downscaled 21^{st} century climate conditions together with a hydrodynamic lake model (Lake Clarity Model) and a distributed hydrology model, predicted the following: 1) Lake Tahoe will continue to warm and its thermal stability will continue to increase; 2) increasing thermal stability will suppress vertical mixing and lake water column turnover; and 3) anoxic conditions within the bottom waters could result in a potentially significant release of soluble reactive phosphorus (SRP) and ammonium-N into the water column from the sediments. If this sequence of geochemical events were to occur in Lake Tahoe sometime in the future, the responses would include a variety of deleterious biological impacts including increased primary production rates, which would impact lake clarity.

INTEGRATING CLIMATE SCIENCE WITH POLICY

The vulnerability assessment of potential system impacts to climate change is a useful criterion to frame the available science in a context relevant for decision makers. The level of vulnerability and associated confidence was determined from the available scientific information for priority expected impacts to Lake Tahoe systems (Table ES. 5). Table ES.5 also assesses the outcome of potential adaptation actions, projecting the degree to which their implementation will lessen the probability or severity of the expected impact.

System	Expected impacts	Degree of vulnerability to impact	Vulnerability assessment confidence	Can the impact to system be lessened by adaptation actions?
Forest	Increased risk of wildfire frequency, extent, and intensity	High	Moderate	*Yes* Example: Reduce fuels
	Shift in the distribution and range of forest flora and fauna	High	High	*Maybe* Example: Increase habitat connectivity
	Increased tree mortality	High	Low	*Yes* Example: Forest thinning[25]
	Reduced forest biodiversity	High	Low	*Unknown* Multiple non-climatic factors and interactions influence biodiversity
Riparian (SEZ)	Changes in soil moisture dynamics	High	High	*Maybe* Example: Maximize groundwater recharge
	Increased erosion risk	High	Low	*Yes* Example: Protect banks; Restore channels
	Increased stress on coldwater species	High	High	*Maybe* Example: Maximize groundwater recharge; Manage streams for shading

System	Expected impacts	Degree of vulnerability to impact	Vulnerability assessment confidence	Can the impact to system be lessened by adaptation actions?
Riparian (SEZ)	Reduced riparian (SEZ) biodiversity	High	Low	*Unknown* Multiple non-climatic factors and interactions influence biodiversity Example: maintain lake-stream connectivity
Built environment	Increased flooding risk	High	Moderate	*Yes* Example: Improve Infrastructure
	Degraded stormwater quality	Low	High	Stormwater quality has a moderate to low sensitivity to climate change and is strongly controlled by human actions
Lake Tahoe	Reduced frequency of water column turnover	High	High	*No*
	Increased risk of low dissolved oxygen in deep water column	High	High	*Maybe* Example: Reduce loading of limiting nutrient (P species) to Lake
	Reduced lake biodiversity	Uncertain	Moderate	*Unknown* Multiple non-climatic factors and interactions influence biodiversity
Water supply	Increased risk of water use conflicts	High	High	*Yes* Example: Conserve water; Maximize groundwater recharge

Table ES.5. Vulnerability assessment summary of expected climate change impacts. The potential for adaptation actions to lessen the potential vulnerability and examples are provided where relevant.

Vulnerability is the susceptibility of a system component to harmful impacts due to climate change. The vulnerability of systems to specific climate change impacts is determined by combining sensitivity and the natural adaptive capability of the system. Effective adaptation actions can reduce the vulnerability of systems to the potential future climatic conditions. Whenever possible, the level of confidence associated with specific climate change projections and/or impacts should be considered in a process to select amongst potential adaptive measures. Collation of climate change science into an accessible format should be an ongoing effort as new information becomes available and the adaptation process evolves over time to incorporate new perspectives, priorities and tools. Table ES.5 also assesses the outcome of potential adaptation actions, projecting the degree to which their implementation will lessen the probability or severity of the expected impact.

CHAPTER 1 - INTRODUCTION

There is now scientific consensus that the temperature of the earth has been increasing more than natural climatic cycles can explain and that this warming is due to human activities (IPCC, 2007; Oreskes et al., 2004). Scientists are measuring various indications of climate and projected climate changes are expected to have a number of negative impacts on the natural and socioeconomic systems throughout the world if no actions are taken.

The two basic ways in which communities can respond to climate change are mitigation and adaptation measures. Mitigation measures are policies made to reduce greenhouse gas emissions locally, regionally and/or globally. Mitigation measures are long-term source control practices to limit release of greenhouse gases into the atmosphere. While mitigation approaches are a critical long-term strategy for reducing the potential magnitude of human-induced climate changes, some of the changes projected to occur may not be avoidable due to the amount of greenhouse gasses that have already been loaded into the atmosphere. Adaptation measures consist of the implementation and/or reprioritization of specific natural resource management actions that are assumed to reduce the future impacts of global climatic conditions on the function and/or health of resources.

The creation of effective policy (directives) and adaptation strategies (actions) will be facilitated by an approach to communicate scientific information specifically designed to meet the needs of managers and decision makers. Climate-driven changes have already been detected in the Lake Tahoe Basin based on historic climatic records and will affect a range of management sectors in Lake Tahoe including forestry, recreation, watershed management, water quality, and water supply. Harmful impacts of climate change can be lessened if stakeholders and resource management agencies incorporate the capacity to adapt their planning based on knowledge of how climate change is likely to affect those systems. Effective responses to change will depend on the ability of managers to assess the impacts at relevant spatial and temporal scales, incorporate this information into their decision making process, and develop and implement strategies for adaptation. Development of effective strategies will rely on resource managers' understanding of:

- Fundamental concepts of climate change science,
- How climate change projections are likely to affect local systems,
- The uncertainties associated with climate projections and system responses in the future, and
- A model for incorporating new information into adaptation strategies as it emerges.

This document is a synthesis of the existing global climate change science as relevant to the resource managers and decision makers in Lake Tahoe. Its purpose is to serve as an informational source to facilitate an informed and collaborative planning approach between agency staff, scientists, consulting groups, and stakeholders as the Lake Tahoe community begins to incorporate climate change considerations into future aquatic resource management. It has been prepared using funding by the Army Corps of Engineers (ACOE) and is one portion of the development of an initial adaptation strategy effort for the Lake Tahoe aquatic resource managers. This synthesis, as well as the broader Adaptation Strategy effort using ACOE funding, provides a preliminary structure and process that allows Lake Tahoe resource managers to document and explore the potential impacts and responses for other Lake Tahoe systems in the future.

While projected climate changes will undoubtedly affect a great number of physical, human, and socioeconomic systems, due to limited resources the scope of this synthesis primarily focuses upon the physical and human systems within Lake Tahoe that are directly related to watershed health, aquatic ecosystems, and water resources.

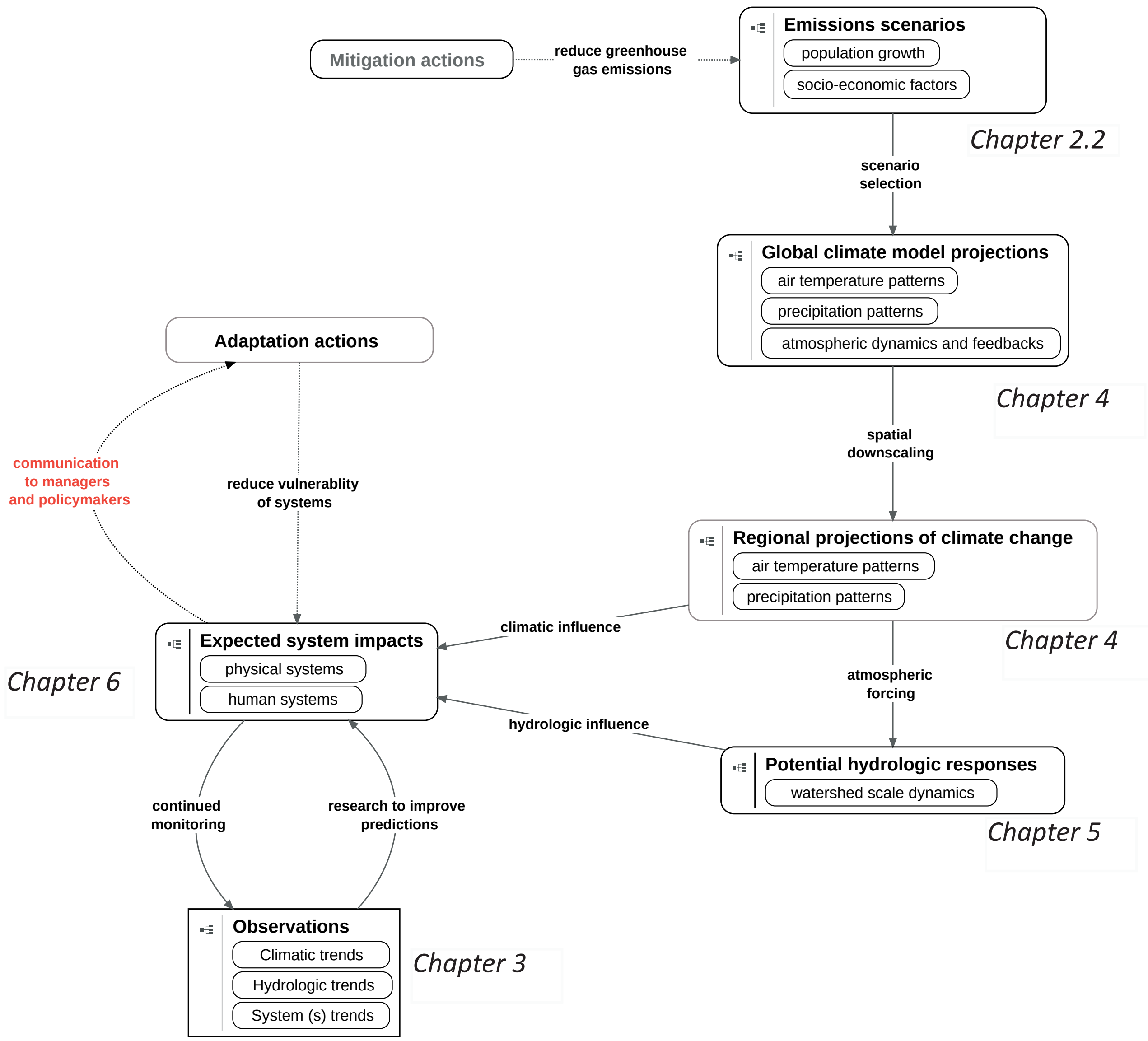
It contains information relevant to the Lake Tahoe resource management community for understanding climate change concepts and how projected changes are likely to influence aquatic and watershed systems in the Lake Tahoe Basin.

1.1 SYNTHESIS APPROACH AND ORGANIZATION

The array of available climate change science information has been organized and presented in a manner that makes it relevant and accessible to the Lake Tahoe resource management community. The information synthesis process involved compilation of scientific literature, technical reports, web-based resources, and recent conference presentations into an online database to facilitate remote collaboration amongst project team members. After a cursory review of the scientific literature, a preliminary science synthesis was presented at the first meeting of the Tahoe Climate Change Working Group on January 14, 2010. A technical advisory team consisting of Lake Tahoe Basin science advisors has provided review, comments and suggestions at key milestones during this synthesis development, including the initial bibliography, science synthesis outline, and drafts of each chapter prior to draft release to the Working Group. Subsequent to the working group meeting three additional scientists with expertise in forest ecosystems were engaged to review the forest impacts section of the synthesis.

A primary objective of this synthesis is to clarify the connections between projected global climate changes and potential future impacts to Lake Tahoe physical and human systems. Figure 1.1 is a conceptual model summarizing the linkages between global climate change projections, potential system impacts, and management and policy actions implemented to reduce system vulnerability to climate changes and/or reduce future greenhouse gas emissions. The right side of the diagram summarizes the information and data flow used to develop future projections of climate conditions in Lake Tahoe over the next century. Climate projections from a variety of models and emission scenarios can be used to predict potential future watershed hydrologic responses. Climatic and hydrologic conditions influence physical and human systems, and thus potential future climatic conditions can be used to estimate potential impacts to aquatic system components such as riparian biodiversity, Lake Tahoe circulation dynamics or water supply. Long-term monitoring will continue to validate and improve the predictions of future impacts due to global climate change. Existing information regarding the sensitivity and adaptability of Lake Tahoe systems to climate change is communicated to managers and policy makers to inform the prioritization of adaptation strategies, mitigation measures and associated policies. This science synthesis is the primary means by which the current state of climate science knowledge relevant to Lake Tahoe aquatic systems is communicated to managers and policy makers.

The organization of this synthesis follows the scientific components within Figure 1.1. Chapter 2 provides a basic overview of climatology and how human activities are impacting global climate and summarizes the existing science of what and how future emissions scenarios are developed and used to predict future global, regional and local climatic conditions. This chapter also contains a discussion of sources of uncertainty associated with climate modeling. Chapter 3 provides a number of global climate model projections of the future of air temperature, precipitation, and atmospheric patterns throughout California and the Sierra Nevada. Chapter 4 summarizes a number of recent climatic patterns within the Lake Tahoe Basin that suggest local warming patterns over the past several decades. Chapter 5 presents the expected future hydrologic responses predicted using regional and local modeling techniques. Chapter 6 reviews a number of expected future impacts to Lake Tahoe physical and human systems that result from climatic changes and associated hydrologic responses. Chapter 7 proposes an organizational structure to evaluate climate change impacts in the Lake Tahoe Basin relative to system sensitivity, adaptability, and vulnerability, including a consistently applied qualitative assessment of confidence for each impact.



A diagram summarizing the linkages between global climate change projections, potential system impacts, and management and policy actions implemented to reduce system vulnerability to climate changes and/or reduce future greenhouse gas emissions. The purpose of this science synthesis is to communicate the existing science of potential Lake Tahoe impacts of global climate change to managers and policy makers. The relevant chapters of the science synthesis are noted.

CLIMATE CHANGE LINKAGE SUMMARY DIAGRAM

FIGURE 1.1

CHAPTER 2 – THE SCIENCE OF GLOBAL CLIMATE CHANGE

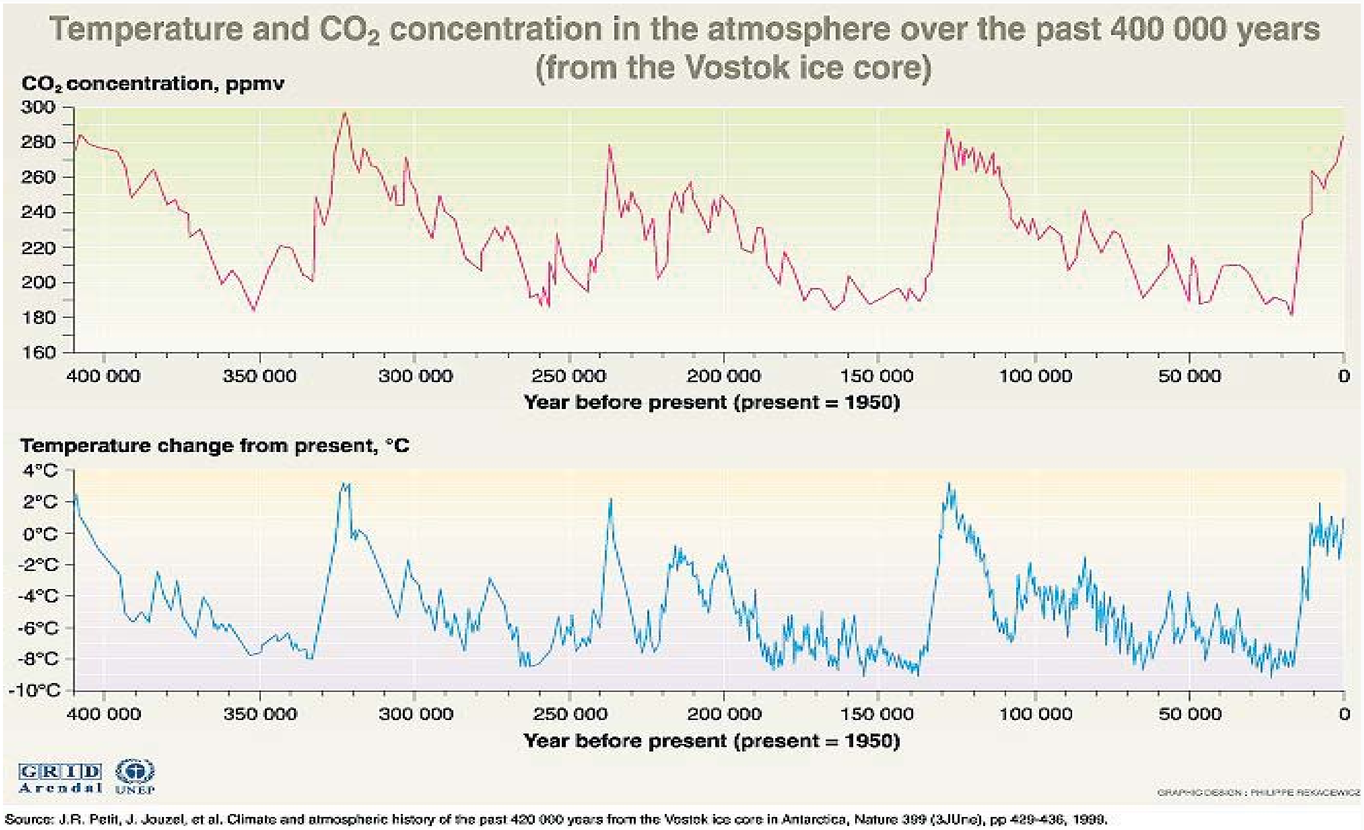
Understanding how global climate change will affect Lake Tahoe systems requires a basic understanding of climate change science. Much of climate change science practice relies on outcomes from the Intergovernmental Panel on Climate Change (IPCC), which has synthesized climate change science on a global scale since 1997. The IPCC brings together researchers from across the globe, organized into working groups. They assess the breadth of climate change related material published in the scientific literature and condense it into comprehensive and objective reports, detailing the current state of knowledge. Approximately 400 experts from some 120 countries are directly involved in drafting, revising and finalizing the IPCC reports and another 2,500 experts participate in the review process. The outcomes from the IPCC have been determining scientific consensus on certain questions, ascribing levels of confidence to particular elements of future climate change, and providing emissions scenarios and guidelines employed by researchers all over the world.

2.1 EARTH'S RECENT CLIMATE PAST AND 20TH CENTURY CHANGES

Over the last 400,000 years the earth's climate has been unstable, with substantial changes in temperature over time. There is evidence in the geologic record of the planet moving from a relatively warm climate to an ice age in a time span of only a few decades (Figure 2.1). On geologic time scales (e.g., >10,000 years), the earth's climate is primarily controlled by changes in the amount of solar energy that reaches the planet's upper atmosphere and the surface and how much is reflected back into space. There have been five known ice ages (times of long-term temperature reduction when ice persists on the polar caps) in the earth's history that can be measured in the geologic record of the past 540 million years. Today, the planet is currently within an inter-glacial (relatively warm) period within the Quaternary Ice Age that began about 2.58 million years ago and peaked during the last 'glacial maximum' approximately 20,000 years ago. Ice core data show that the last 400,000 years have consisted of short inter-glacial periods (10,000 to 30,000 years) about as warm as the present, alternated with longer (70,000 to 90,000 years) glacial periods that were substantially colder than present.

Glacial and inter-glacial periods result from changes in the amount of solar radiation reaching the earth's surface. These changes can be caused by internal processes that affect the planet's albedo (reflectivity) or atmospheric composition such as volcanism, shifting positions of continents, and uplift of vast mountain regions; or by external processes such as solar energy output, meteorite collisions, and changes in earth's orbital geometry. Reduced solar activity from the 1400s to the 1700s was likely a key factor in the slight cooling of North America, Europe and probably other areas around the globe during this period. Volcanic eruptions eject gasses that condense into aerosols that scatter light in the atmosphere, resulting in less energy reaching the surface. The Mount Pinatubo eruption (1991) in the Philippines created such an aerosol haze and is believed to have lowered global temperatures by approximately 0.25^{o}C for a few years following the eruption (Hansen et al., 1996). A similar effect may have also been responsible for a cooling anomaly observed in Lake Tahoe during 1982-83 with the eruption of El Chichón (Chiapas, Mexico) in the spring of 1982 (Coats et al., 2006). The orbital characteristics of axial precession, axial tilt, and orbital eccentricity (so called Milankovitch cycles) vary on time scales of 26,000; 41,000; and 100,000 years and their combined effects correlate well with the history of glacial and interglacial periods on earth.

Based on the evidence available, it is unlikely that global mean temperatures have varied by more than 1°C over 100 year periods for the past 400,000 years (IPCC, 2007). Between the years 1900 and 2000, temperatures have warmed by 0.74 ± 0.18 °C and are expected to continue rising further and faster in the coming century (IPCC, 2007). A composite proxy-based northern hemisphere reconstruction completed by Mann et al. (2008) of



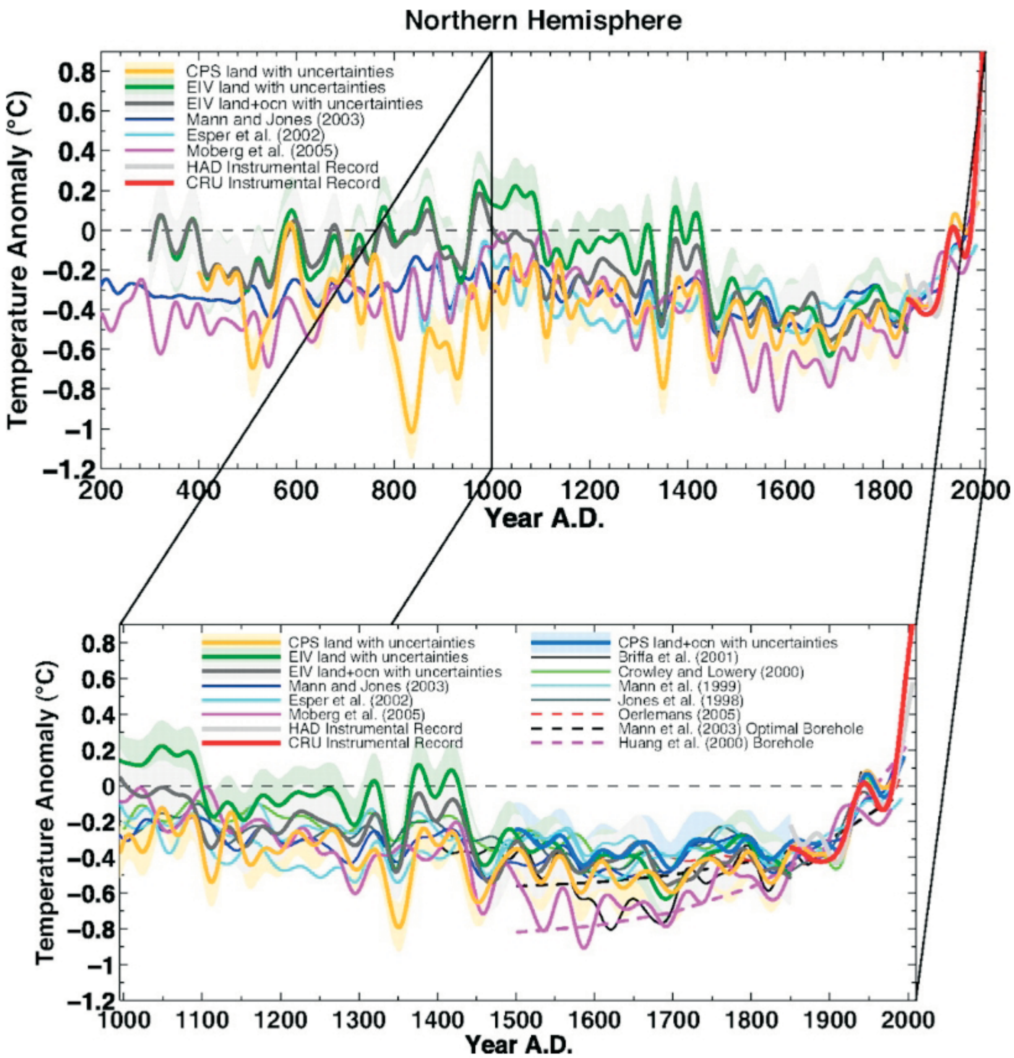
Temperature and CO_2 concentrations over the past 400,000 years. The graphic indicates a strong association between temperature and CO_2 levels. It is unlikely that global mean temperatures varied by more that 1°C in a century during this period. Source: Petit et al., 1999 temperature anomalies (departure from the long-term average) for the last 2000 years for numerous proxy (e.g., tree rings, corals, ice cores) and instrumental datasets illustrates the importance of the recent temperature rise (Figure 2.2). The lower portion of Figure 2.2 shows the composite reconstruction along with other temperature reconstructions published in peer-reviewed journals and instrumental data - note the amplitude of the recent temperature anomaly relative to the past 1000 years. The Mann et al. (2008) work is an example of the substantial body of evidence that points to dramatic recent temperature changes despite the substantial uncertainties involved. Such work has contributed to the IPCC conclusion that the temperature of the earth has been increasing at a rate that is greater than can be explained by natural climatic cycles and excluding atmospheric changes resulting from fossil fuel burning over the last century (IPCC, 2007).

Every year the sun delivers an average of 340 watts/m^2 of energy to the earth's surface and one third of the solar radiation that hits the earth is reflected back to space (Figure 2.3). Of the remainder, the atmosphere absorbs some, while the land and oceans absorb most. The earth's surface becomes warm and as a result emits infrared radiation. Greenhouse gases trap the infrared radiation, thus warming the atmosphere and allowing the atmosphere to reradiate infrared radiation back to the earth's surface. This is the "greenhouse effect". Naturally occurring greenhouse gases include water vapor, carbon dioxide, ozone, methane and nitrous oxide. In addition to the greenhouse gasses, the amount of aerosols in the air has a direct effect on the amount of solar radiation hitting the earth's surface. Aerosols scatter short-wave radiation in the atmosphere and may have significant local or regional impacts on temperature. Water vapor can both trap infrared radiation in the atmosphere (greenhouse gas) and reflect solar radiation back into space (upper white surface of clouds).

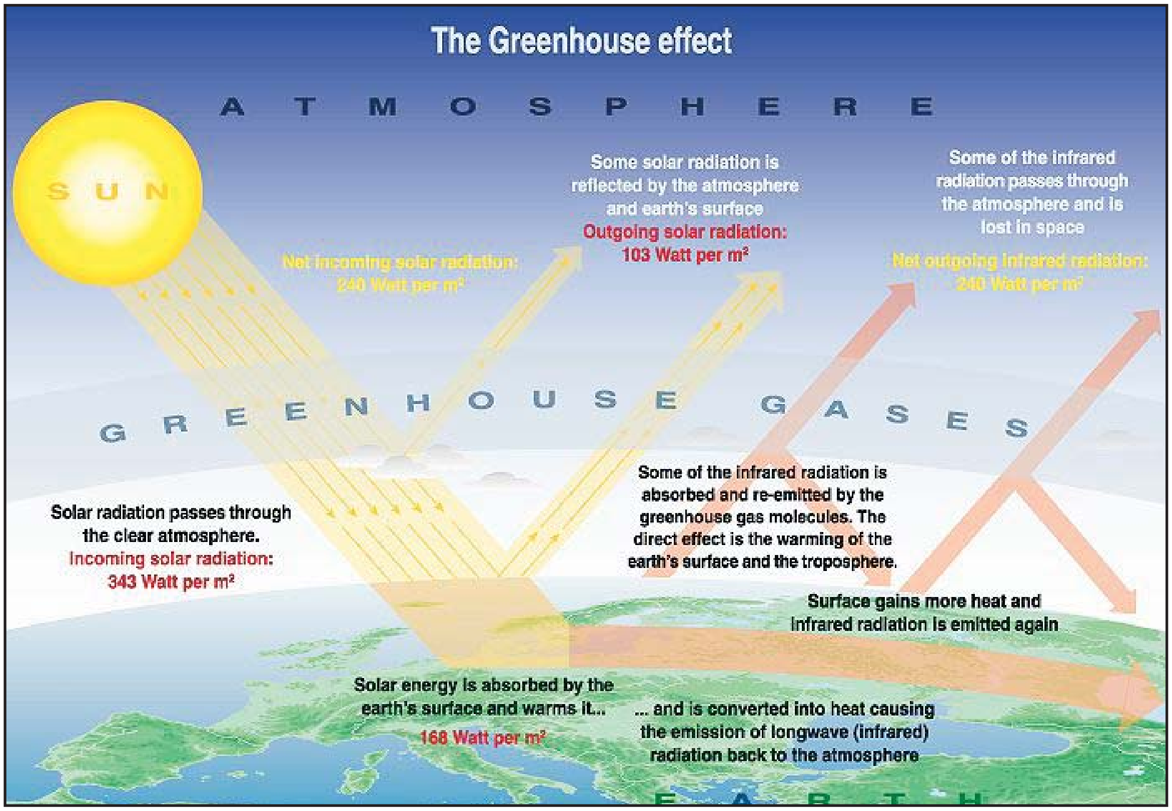
There is scientific consensus that the recent episode of 'global warming' is due to human activities and that fossil fuel burning is the primary cause because it effectively transforms carbon sequestered in the earth as oil and coal deposits into carbon dioxide at a much faster rate than natural processes allow. The radiative forcing (or reflection back to earth of infrared radiation due to higher greenhouse gas concentrations) since the pre-industrial era is positive (warming) with a small uncertainty range. Without any greenhouse gases the global average temperature would be around -20^{o}C. Over the last 100 years, human actions have significantly increased greenhouse gas concentrations as a result of burning fossil fuels (coal, oil and natural gas). Land use practices and removal of large areas of vegetation, such as deforestation and conversion to agriculture, on a global scale have reduced the uptake of carbon dioxide (CO_2) by plants during photosynthesis. The largest proportion of carbon dioxide emissions comes from energy production, industrial processes and transportation activities in industrialized countries.

Figure 2.4 provides some of the most compelling evidence that the combined human actions of fossil fuel burning and land use conversion has resulted in increased levels of carbon in the atmosphere above the levels that we can measure in the geologic record. Figure 2.4 illustrates the recent increase in atmospheric CO_2 relative to changes observed through geologic time. Over the past 400,000 years the maximum CO_2 levels in the atmosphere have not exceeded 300 ppmv (parts per million volume) during interglacial periods. However, in the last 200 years the CO_2 concentrations have not only exceeded levels never before seen, but have risen at an unprecedented and alarming rate and today are measured over 390 ppmv on a continued upward trend (NOAA Earth System Research Laboratory [ESRL] website: www.esrl.noaa.gov/gmd/ccgg/trends/).

Another example of measured CO_2 changes is the time series of CO_2 concentrations in the atmosphere measured at an altitude of about 4,000 meters on the peak of Mauna Loa mountain in Hawaii since 1958 (Figure 2.5). The measurements at this location are remote from local sources of pollution and constitute the longest direct measurement of CO_2 in the atmosphere (Keeling, 1976). The measurements clearly show that atmospheric concentrations of CO_2 are increasing. The mean concentration of approximately 316 ppmv in 1958 has risen to above 390 ppmv in 2010 (see Figure 2.5). The annual variation in CO_2 concentrations (red line) is caused by uptake



Northern hemisphere composite temperature reconstructions and estimated 95% confidence intervals for 'CPS' and 'EIV' reconstruction methods. Shown for comparison are published New Hampshire reconstructions, which are centered to have the same mean as the overlapping segment of the Climate Research Unit instrumental New Hampshire land surface temperature record 1850–2006. The temperature record data have been scaled to have the same decadal variance as the composited series, excluding the borehole-based reconstructions, during the overlap interval. Source: Mann et al., 2008



This graphic explains how solar energy is absorbed by the earth's surface, causing the earth to warm and emit infrared radiation. The greenhouse gases then trap the infrared (longwave) radiation, warming the atmosphere. Source: UNEP, 2002

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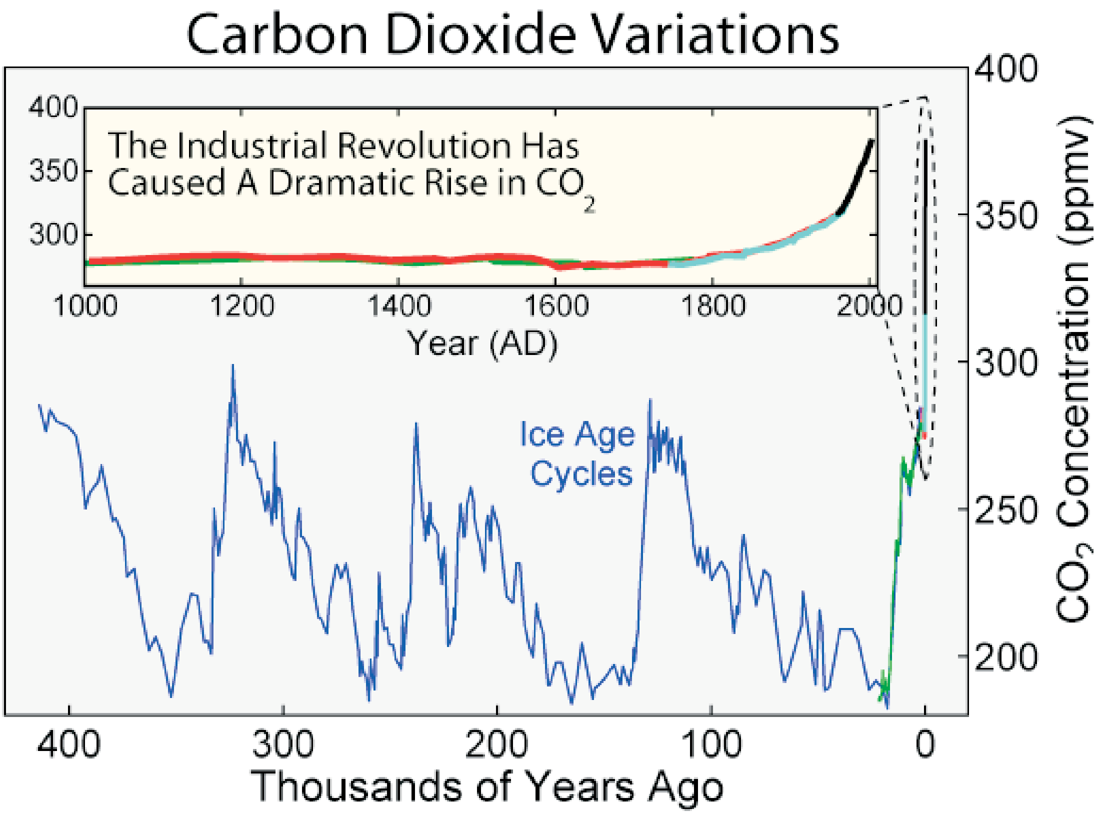
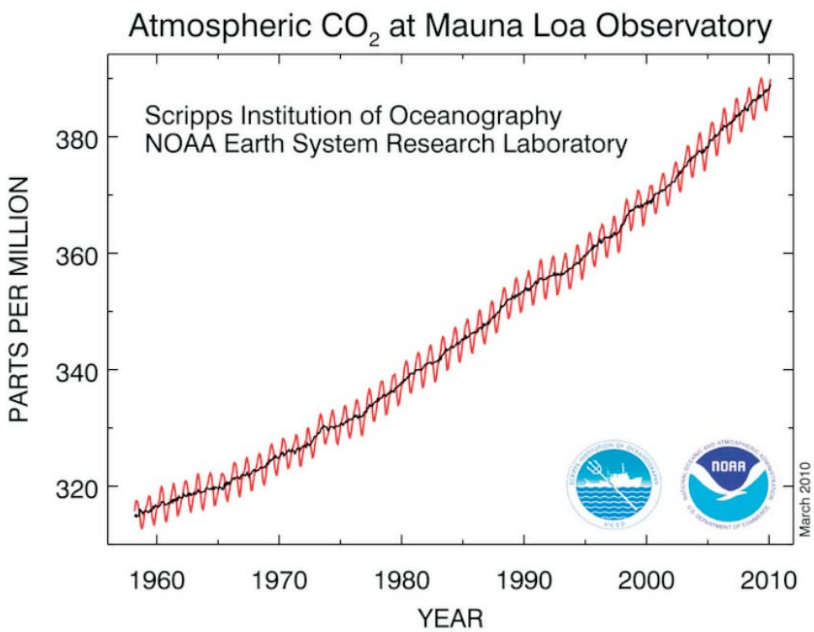


This figure shows the variations in concentration of carbon dioxide (CO_2) in the atmosphere during the last 400 thousand years as measured from ice cores. Throughout most of the record, the large changes can be related to glacial/interglacial cycles within the current ice age.
Blue = Vostok ice core (Petit et al., 1999); Green = EPICA ice core (Monnin, et al., 2004); Red = Law Dome ice core (Etheridge et al., 1998); Cyan = Siple Dome ice core (Neftel et al., 1994); Black = Mauna Loa Observatory, Hawaii (Keeling and Whorf, 2004). Source: Rohde, 2006



CO_2 concentrations at the Mauna Loa Observatory, Hawaii. Data are reported as a dry mole fraction defined as the number of molecules of carbon dioxide divided by the number of molecules of dry air multiplied by one million (ppm). The recent rise in CO_2 is alarming given the correspondence in the geologic record between atmospheric CO_2 concentrations and global temperatures (see Figure 2.1). Source: Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/)

by growing plants and the black line is the seasonally corrected trend. The recent rise in CO_2 is alarming given the correspondence observed in the geologic record between atmospheric CO_2 concentrations and global temperatures (see Figure 2.1).

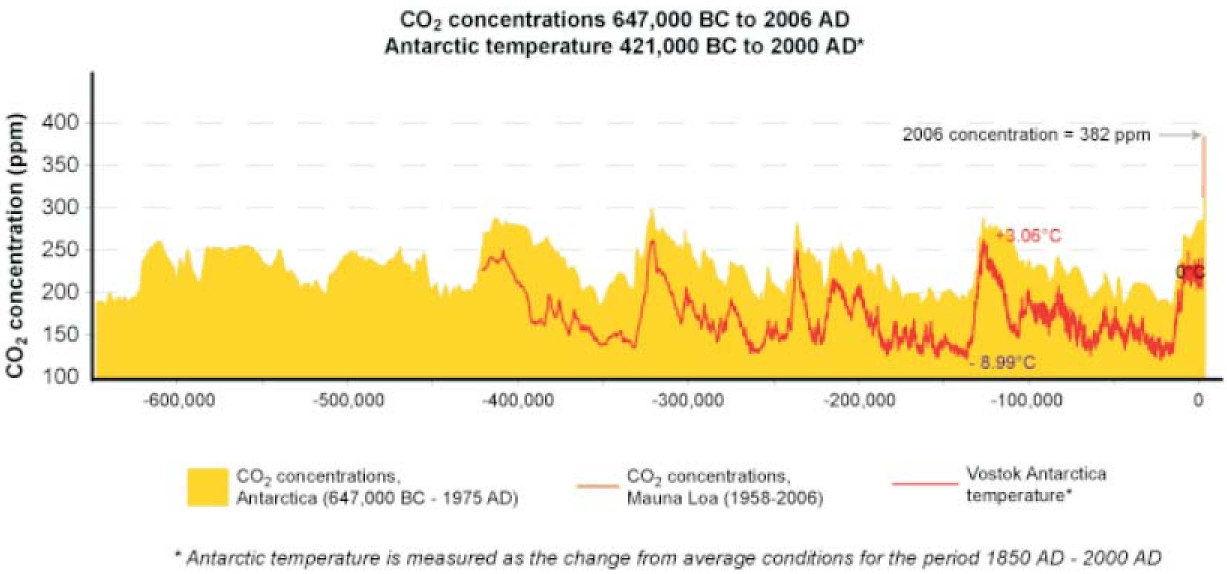
When CO_2 data from Mauna Loa is combined with temperature data from ice core measurements taken in Antarctica, there is good correspondence between estimates of atmospheric CO_2 levels and temperature changes over the past 421,000 years (Figure 2.6). Elevated CO_2 levels do not initiate global temperature changes, but rather lag behind them by perhaps 600-1000 years (Caillon et al., 2003) and tend to perpetuate and amplify warming that has been initiated primarily by orbital variations (the Milankovitch cycles). Increased CO_2 levels create a positive feedback involving ice sheet albedo (less ice = less reflection of sunlight = warmer temperatures) and CO_2 concentrations (higher temperatures lead to movement of CO_2 from the oceans to the atmosphere, which leads to warmer temperatures). As the ocean warms, the solubility of CO_2 in water falls (Martin, 2005), causing the oceans to release CO_2 into the atmosphere. The process takes around 800 to 1000 years, so CO_2 levels are observed to rise around 1000 years after the initial warming (Monnin, 2001; Mudelsee, 2001).

2.2 PREDICTING FUTURE CLIMATE CHANGE

Climate change refers to variations in the atmosphere that can be measured over long time scales from decades to millions of years, in contrast to short term variations that are reflected as daily or weekly changes in weather. Thus, climate can be thought of as the weather averaged over decadal time scales. Information about global climate change is often in the form of warming trends projected into the future (often up to the year 2100) and across space that result from global climate modeling experiments. Global climate models rely on the theoretical understanding of atmospheric dynamics and chemistry coupled with surface systems (ocean, land, ice) and calibrated with observations made in the past to create a digital representation that can be used in heuristic experiments with 'what if' scenarios of the future climate. The outputs of global climate change models include future air temperature and precipitation patterns given a range of possible greenhouse gas emissions scenarios. The ability to anticipate future events, even with a substantial degree of uncertainty, can help us to make better decisions now in order to potentially reduce the impacts of climate change to natural and socioeconomic systems in the future.

EMISSIONS SCENARIOS

Emissions of green house gasses (GHGs) are a critical element of future atmospheric composition that can change atmospheric processes and interactions between the earth's atmosphere, oceans, land surface, and ice in the future. Since we do not know precisely what the future local, regional or global emissions will be as a result of developing technologies and policy decisions, climate projections of future conditions include a range of emissions scenarios. Emerging technologies could accelerate the impacts or mitigate the effects of greenhouse gas emissions, depending on how they are applied. Emissions scenarios define how the inputs to the atmosphere change over time. Numerous human activities increase GHG (e.g., methane, nitrous oxide, carbon dioxide, etc.) concentrations in the atmosphere including the burning of fossil fuels, agriculture, deforestation, automobile exhaust, and others. One of the primary reasons for developing emissions scenarios is to enable coordinated studies of climate change, climate impacts, and mitigation options and strategies (IPCC, 2007). The IPCC used an approach detailed in its Special Report on Emissions Scenarios (SRES) for its Fourth Assessment (IPCC, 2007), which acknowledges that atmospheric GHG levels will depend on policy and development outcomes.



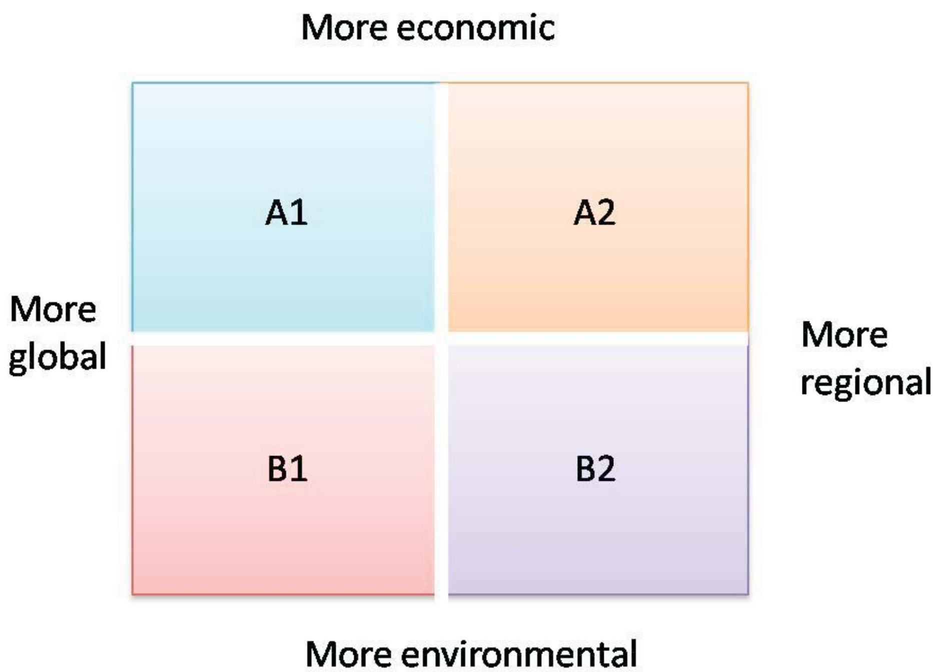
Fluctuations in temperature (red line) and in the atmospheric concentration of carbon dioxide (yellow) over the past 649,000 years. The vertical red bar at the end is the increase in atmospheric carbon dioxide levels over the past two centuries and before 2007. Source: IPPC, 2007

Emissions scenarios are driven by variations in population projections, economic development and structural/technological changes and the interactions between these factors. The scenarios differ in how they handle specific elements of the controlling factors and how that variation is distributed across the globe and over the next century. Any of the 40 scenarios used in the SRES necessarily includes subjective elements and is open to various interpretations. Each scenario involves both qualitative and quantitative components; they have a narrative component called "storylines" and a number of corresponding quantitative scenarios for each storyline. The SRES scenarios were developed as quantitative interpretations of the four alternative storylines that represent possible futures with different combinations of driving factors and exclude only outlying future pathways reported in the scientific literature. The 40 SRES scenarios are grouped into families based on storyline characteristics relative to the nature of development and economic growth in the future. Scenarios in families A1, A2, B1, and B2 are positioned differently relative to axes that represent economic versus environmentally oriented growth and whether the focus of growth is at regional (uneven with a large gap between now-industrialized and developing parts) or global spatial scales (Figure 2.7). Since probabilities cannot be assigned to individual SRES scenarios at this time there is no consensus by the experts on the single, most likely emissions scenario.

For the majority of references cited in this synthesis, the B1 and A2 emissions scenarios are used to bracket the high and low projections, respectively. The lowest emissions scenario (B1) is considered an optimistic future emissions condition as result of significant reductions in the current GHG production rate worldwide. The actual achievement of the B1 scenario would require significant future decreases in GHG concentrations from the current rate of production as a result of a shift toward less carbon intensive economies in both the developed and developing world. A2 is considered the medium high emissions scenario (see Table 2.1), which assumes a lack of world cooperation in working towards future sustainable development. A2 represents a future GHG situation in which economic growth is uneven with a large gap between now-industrialized and developing parts of the world (Canyan et al., 2009). The A2 world supposes less international cooperation than the A1 or B1 worlds, with people, ideas, and capital less mobile so that technology diffuses more slowly than in the other scenario families. The 2006 California Scenarios Assessment additionally included a ‘fossil fuel intensive’ or high emissions scenario (A1fi), which assumes that current rate of CO_2 emissions continues unabated. Table 2.1 compares the different models and assumptions about socioeconomic conditions in the future related to population growth and technological advancements and choices used in most of the climate modeling studies associated with the different emissions scenarios.

Driving Factor for 21st Century Growth	**Emissions Scenario**		
	A1Fi high	**A2 medium-high**	**B1 low**
Population growth	low	high	medium
GDP growth	very high	medium	medium
Energy use	very high	high	medium
Land use changes (deforestation)	low-medium	medium-high	medium
Resource availability (fossil fuels)	high	low	medium
Pace and direction of technological change to adopt carbon reduction solutions	rapid	slow	medium
Focus of Future Change	regional development	coal, oil and gas	‘business as usual’

Table 2.1. Comparison of driving factors of the three emissions scenarios used in the California Scenarios Assessments conducted in 2006 and 2008 (Source: IPCC, 2007).



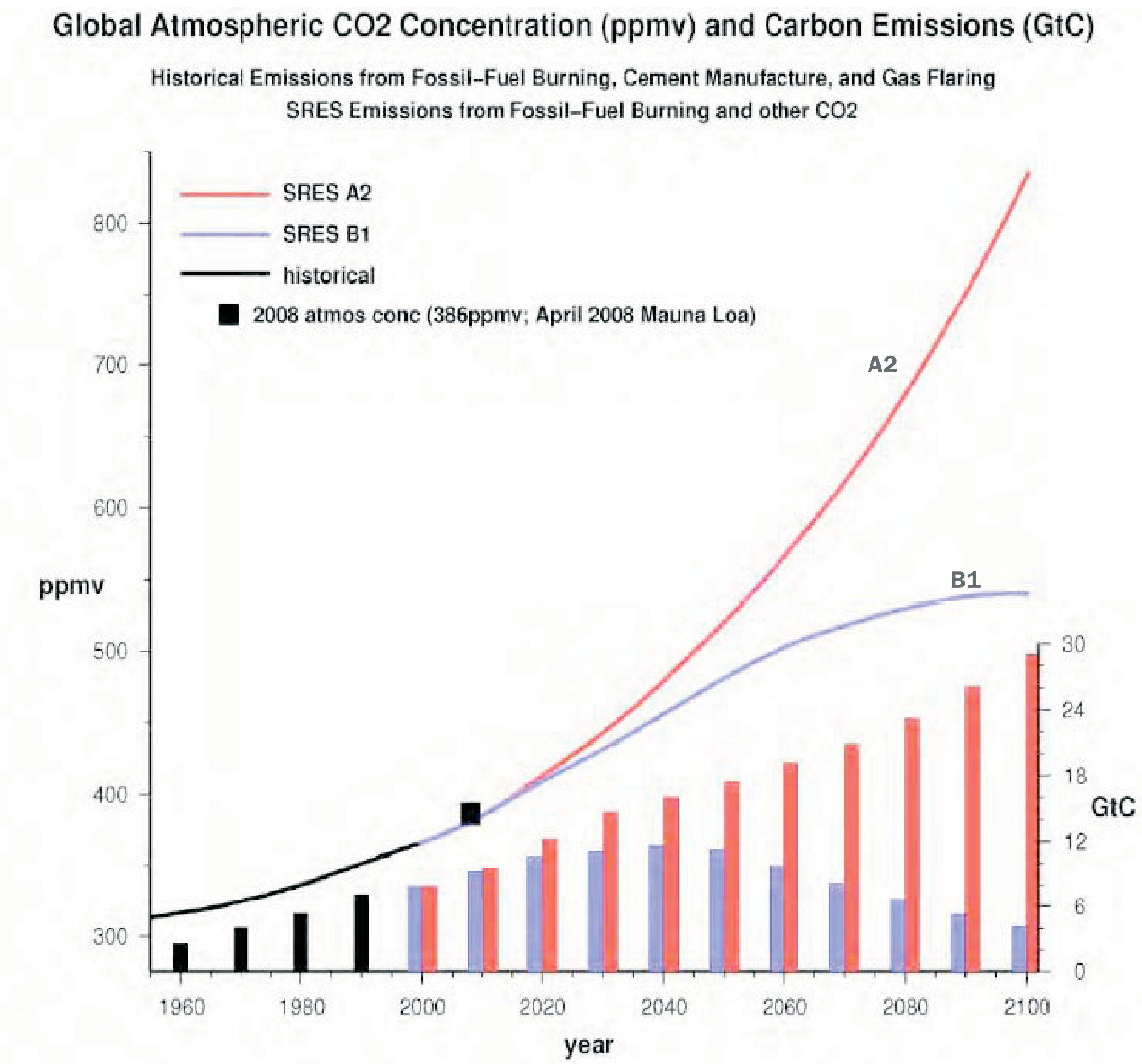
A schematic representation of the SRES scenario families. The A1 and A2 families have a greater economic focus than B1 and B2, which are more environmental, whilst the development focus of A1 and B1 is more global compared to the more regionally oriented A2 and B2. Examples of the quantitative scenario inputs that determine where they are positioned on this diagram include: regionalized measures of population, economic development and energy efficiency; the availability of various forms of energy; agricultural production; and local pollution controls.

The range of emissions scenarios estimate dramatic increases in atmospheric CO_2 concentrations over the next century. All emissions scenarios, even the optimistic B1 scenario, are very likely to have a discernable effect on future climate (Maurer, 2007). Figure 2.8 from Cayan et al. (2009) graphically illustrates the estimated global carbon emissions and atmospheric CO_2 concentration and trajectories of the B1 (low) and A2 (medium-high) scenarios. The B1 scenario assumes that global (including California) CO_2 emissions peak at approximately 10 gigatons per year (Gt/year) in mid-twenty-first century before dropping below current levels by 2100 (Cayan et al., 2008). This yields a doubling of CO_2 concentrations relative to its pre-industrial level by the end of the century, followed by a leveling of the concentrations. The B1 scenario is considered highly optimistic given current global GHG productions, but assumed to be achievable. Under the A2 scenario, CO_2 emissions continue along the current production trajectory and climb throughout the century, reaching almost 30 Gt/year. By the end of the twenty-first century, CO_2 concentrations reach more than triple their pre-industrial levels (see Figure 2.8).

GLOBAL CLIMATE MODELS

Global climate models quantitatively represent changes over time in physical states and dynamics of the atmosphere, ocean, land surface and ice surface, and the interactions between these systems. Atmospheric and Oceanic General Circulation Models (GCMs), which solve numeric equations that describe fluid motion in the atmosphere and oceans, are key components of global climate models. Global climate models differ substantially in their quantitative treatment of atmospheric/oceanic processes (e.g., ocean-atmosphere heat flux) and how they represent feedbacks between the atmosphere, ocean and land surface (e.g., atmospheric responses to changes in surface albedo). Imperfect knowledge of the processes represented in global climate models has led to a number of different model structures that may perform equally well, albeit for different reasons, when compared with existing climatic or oceanographic data.

Since there are multiple model structures and probable input scenarios available and there is no objective way of deciding between them, it makes sense to use a suite of them in combination to produce an ensemble of projections (e.g., McIntyre et al., 2005). Using model projections in combination with one another allows researchers to assess the feasible range of future climate change projections from different model structures. The California Climate Change Scenarios Assessment (Scenarios Assessment) picked models and emissions scenarios from the IPCC assessment for more intense analysis with the intent of bracketing the high and low ends of predictions from the larger IPCC model ensemble (Cayan et al., 2008b). The Scenarios Assessment initially investigated outputs from three global climate models and three greenhouse gas emissions scenarios in 2006 (Cayan et al., 2008b) and was updated in 2008 to investigate outputs from six models and two emissions scenarios from the Special Report on Emissions Scenarios (SRES). Global climate models used in the Scenario Assessments and other studies referenced in the following chapters are listed in Table 2.2. Lake Tahoe-specific climate change studies frequently use outputs from the GFDL and PCM models.



Global carbon emissions for the historical period (black) and the low SRES B1 (blue) and medium-high SRES A2 (red) emissions scenarios. Bars represent loading to the atmosphere (gigatonnes of carbon, GtC) and lines represent atmospheric CO_2 concentration (parts per million, volume, or ppmv). Scenario A2 assumes little reduction in current emissions patterns globally, whereas scenario B1 assumes a signficant amount of global emission reduction efforts are achieved by 2040 as noted by the asymptotic shape of the B1 curve toward the end of the 21st century. The A2 and B1 scenarios are often used in climate model experiments to bracket the set of plausible future scenarios. Source: Cayan et al., 2009

Model ID	Model Name	Principal Developer	CA Scenario Assessment Year
PCM	Parallel Climate Model	National Center for Atmospheric Research (NCAR)	2006/2008
GFDL	Geophysical Fluids Dynamics Laboratory	National Oceanic and Atmospheric Administration (NOAA)	2006/2008
CNRM	Centre National de Recherches Météorologiques	Centre National de Recherches Météorologiques	2008
CCSM	Community Climate System Model	National Center for Atmospheric Research (NCAR)	2008
ECHAM5/ MPI-OM	Max Planck Institute Model	Max Planck Institute, Earth Sciences and Climate Research	2008
MIROC 3.2	Medium Resolution Model	Center for Climate System Research of the University of Tokyo and collaborators	2008
HadCM3	UK Hadley Center Model	Hadley Center for Climate Prediction and Research	2006

Table 2.2. GCM models used in California Scenarios Assessments and other studies.

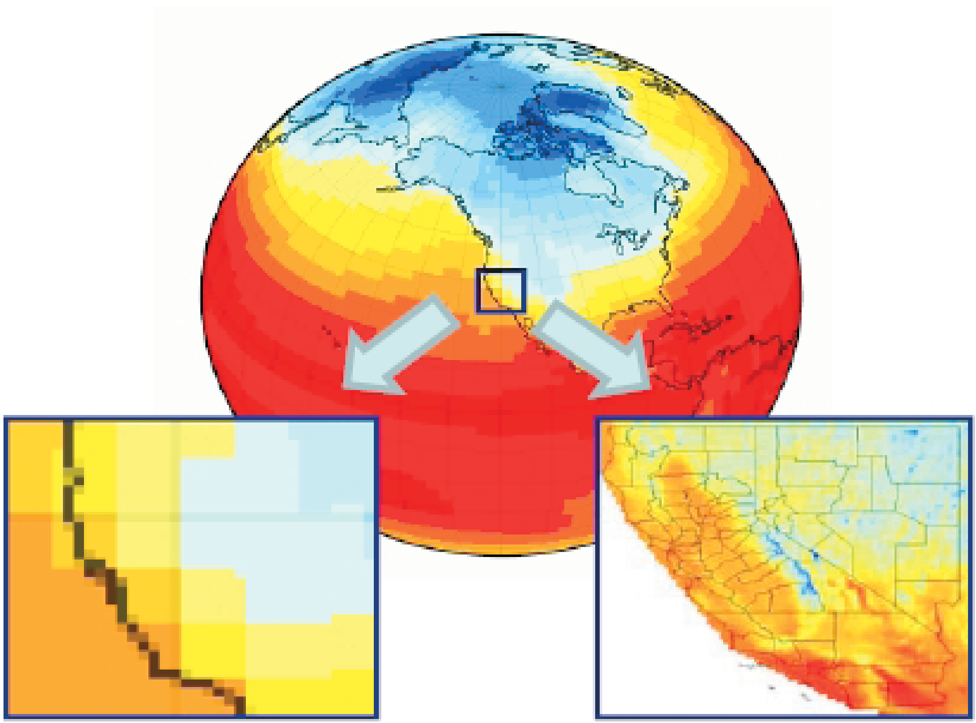
REGIONALIZING GLOBAL CLIMATE PROJECTIONS

The spatial resolution of the outputs from global climate models (100-500 km^2) is too large to adequately meet the needs of regional or local resource management decisions (Johnson and Weaver, 2009). One solution to the problem is to 'downscale' spatially coarse predictions to a scale that suits the process resolution needs of scientists and managers. This can be done using a 'dynamical' approach, which models processes at a finer scale within a global climate model grid cell, or a 'statistical' approach that uses climate model outputs in combination with other locally derived climate information.

The 2009 California Climate Change Scenarios Assessment used two different statistical approaches to generate California and smaller regional-scale predictions from climate model outputs and assessed their performance at reproducing historical data. The two downscaling methods were constructed analogues (CA) (Hidalgo et al., 2008), and bias correction and spatial downscaling (BCSD) (Wood et al., 2004). Both methods have been shown to perform reasonably well by Maurer and Hidalgo (2008). Cayan et al.(2009) report that both methods produce generally comparable downscaled, gridded fields of precipitation and temperature for monthly and seasonal intervals. Figure 2.9 illustrates the difference in grid cell size use by global climate models compared to those that result from downscaling projections for California. Spatial downscaling procedures developed for California can now produce projections for daily temperature and precipitation at spatial scales of approximately 12km^2 (Moser et al., 2009).

CLIMATE MODEL OUTPUTS

Because of the inherent uncertainties involved, outputs from global climate models are best thought of not as discrete predictions of future climate patterns on regional spatial or annual time scales, but rather as possible long-term trend scenarios given a range of possible drivers and conditions of the climate system (Cayan et al., 2009). Climatic model outputs are expressed in summary metrics that represent an overall shift in certain climate variables over decadal time scales (e.g., mean annual precipitation), changes in spatial patterns (e.g., temperature gradients), or 'extreme event' changes (e.g., magnitude, frequency, and return intervals). Changes in climate elements are related to properties of their probability distributions, such as the mean and the variance. Figure 2.10



Schematic showing relative spatial scales of temperature grid cell outputs from global climate models and downscaled data for California. The two lower images show the increase in spatial resolution that results from the downscaling process that can now produce projections at spatial scales of approximately 12 square km. Source: Moser et al., 2009

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SPATIAL SCALE COMPARISON: GLOBAL CLIMATE MODELS AND DOWNSCALED DATA

FIGURE 2.9

illustrates how changes in characteristics of the temperature probability distribution can be interpreted as the increase in the relative likelihood of occurrence of hot weather in California. Most locations in the interior of California show a change to a warmer 100 year three-day mean maximum temperature (maximum three-day average temperature that is likely to occur in the next 100 years), indicated by the change from cooler to warmer colors from left to right in Figure 2.10.

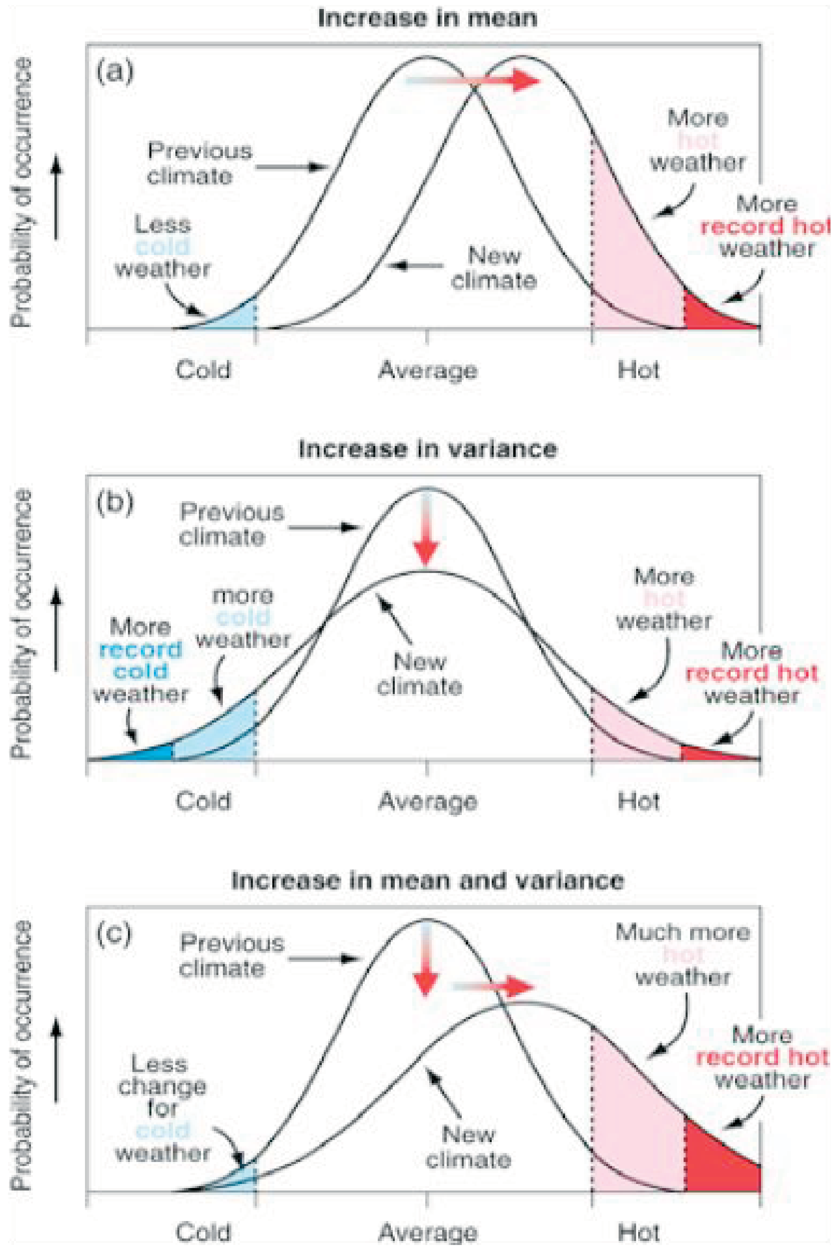
According to the IPCC, climate change impacts are likely associated with 'extreme events' such as sustained droughts, hurricanes, intense rain events, floods, etc. *Extreme* refers to rare events based on a statistical model of climate element probability distributions and can be generally defined as events occurring between 1% to 10% of the time at a particular location over a certain period of time (Trenberth et al., 2007). The public perception of the "climate change" will be influenced by the potential increased frequency of occurrence and relative magnitude of these extreme events. A description of climate model projections in Chapter 5 includes discussion of scientific research related to general predicted climatic patterns and 'extreme events' relevant to Lake Tahoe and the Sierra Nevada region.

CLIMATE PROJECTION UNCERTAINTY

State of the art climate models are not able to provide precise, probabilistic predictions of future climate change at scales useful for regional resource managers (Johnson and Weaver, 2009) due to incomplete scientific understanding of future emission scenarios, global climate processes, data gaps, and the general inherent uncertainties of predicting future climate. The climate system exhibits chaotic behavior and is highly sensitive to very small differences in initial conditions. Since a very small change at one point in time can lead to widely diverging results at a later time, precise long-term predictions are difficult to near impossible. While scientists can forecast the weather days or weeks in advance, the levels of precision and confidence decrease the further away we get from a time or place that we can measure atmospheric variables. Long-term climate projections from models are therefore necessarily spatially and temporally coarse and contain high degree of uncertainty.

Confidence ranking	Description
High	General scientific agreement of conclusion that is supported by a number of monitoring data, modeling results, research or best available scientific information.
Moderate	Scientifically supported but consensus or agreement is not present due to lack of information, moderate differences between studies, or limitations for drawing general conclusions from limited scientific information.
Low	Lack of information or directly conflicting results between studies, opinions and/or research findings.

Table 2.3. Ranking scale used to provide simple communication of general confidence of a number of different conclusions presented throughout this science synthesis.



Possible modes of change are illustrated for temperature distribution, including distribution shifts, changes in amplitude, and changes in skew. Source: Mastrandrea et al., 2009

Specific sources of uncertainty in regional projections from climate models include:

- **Deficiencies of process representation, chosen model structures, and parameterizations.** Different structures can be thought of as competing hypotheses about the function of how physical processes drive climate. Global climate models omit characteristics that occur below the spatial and temporal resolution of the model (e.g., convective clouds and thunderstorms) because of current knowledge and computational limits (Oreskes et al., 1994; Beck 2002). Highly complex climatic processes or processes that occur on too small of spatial scales to be fully represented are often replaced by more simple representations (parameterizations).
- **Errors in the model input data (historic precipitation and temperature, future GHG emissions).** Global climate models are very sensitive to the future global emission scenarios, but the range of future GHG emissions is highly uncertain. To put the uncertainty associated with emissions scenarios considered for California projections into context, the estimated emissions growth for the period from 2000 to 2007 has been reported to be greater than the most fossil fuel intensive scenario used in the SRES-IPCC Fourth Assessment (Science Daily, 2008; Raupach et al., 2007).
- **Assumptions associated with the spatial downscaling approach.** Dynamical and statistical downscaling techniques each have limitations for producing finer-scale projections.

Given the uncertainties involved, a suite of projections from different climate models and emissions scenarios with different sets of assumptions provides a range of potential climate outcomes from which similarities and consistencies across model results and future projections can be identified. When using model projections to understand climate change responses, a higher degree of confidence can be assigned to future conditions that are consistently predicted across different models and emissions scenarios than changes estimated from isolated model experiments.

MORE INFORMATION ON CLIMATE CHANGE SCIENCE

Information is available at the following web sites:

- Intergovernmental Panel on Climate Change: www.ipcc.ch
- United Nations Framework Convention on Climate Change: www.unfccc.int
- United Nations Environment Program: www.unep.org
- UNEP/GRID-Arendal: www.grida.no/climate
- Climatewire (a climate news portal): www.climatewire.org
- United States Global Change Research Program: http://www.globalchange.gov/

CHAPTER 3 - OBSERVATIONAL EVIDENCE FOR CLIMATE CHANGE IN THE TAHOE BASIN

Observational evidence for climate change is available at different spatial scales ranging from global to regional for about the past 100-200 years. The extent of these measurements is very short relative to the geologic history of earth's climate system (billions of years). Atmospheric temperature and composition changes that occur over thousands to millions of years are quantified using information from the geologic record, such as oxygen isotope ratios in ice cores. Detecting the signal of climate change locally within the short-term variability of natural systems typically requires measurements over many years or decades.

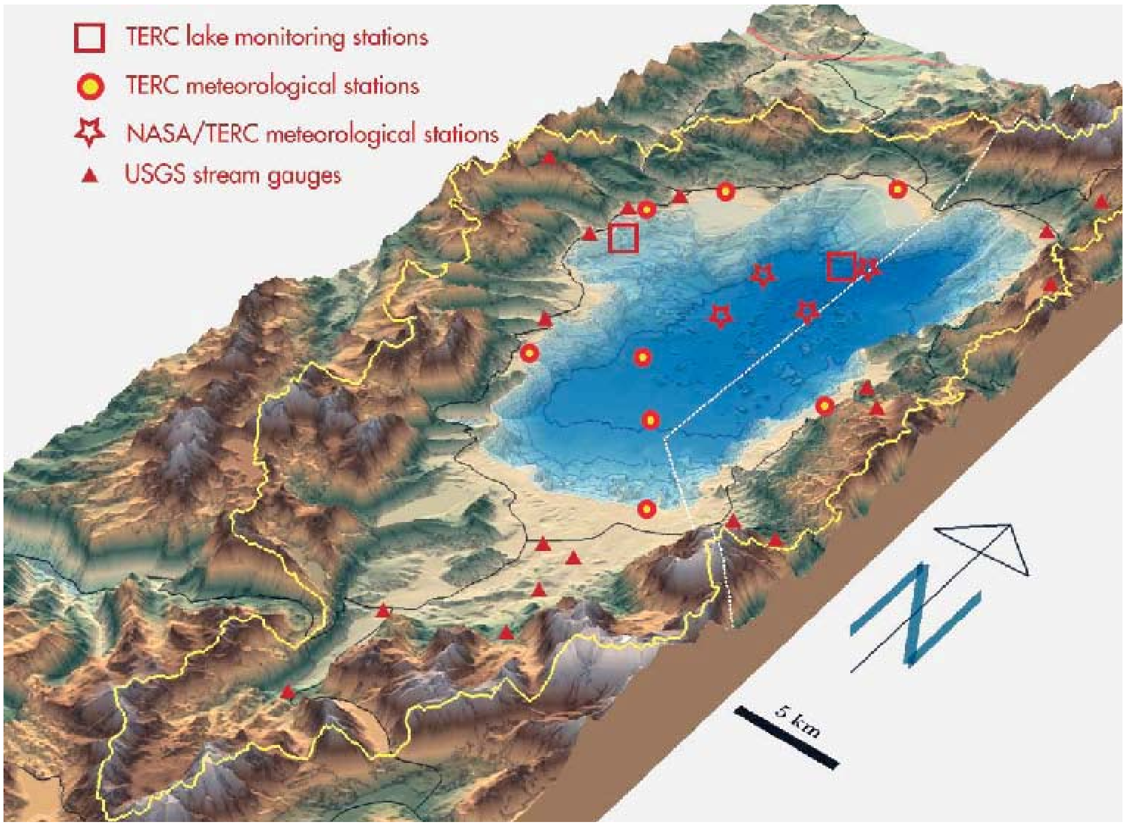
3.1 LONG-TERM MONITORING IN THE TAHOE BASIN

Continuous long-term local records of climatic and hydrologic variables are critical to understanding past climate changes. Data from long-term monitoring programs improve our ability to isolate the inherent natural variability in climate, hydrology and biological systems versus changes induced by human impacts. Evaluation of existing datasets can be used to test hypotheses regarding past climatic patterns and inform our understanding of current trends. Below we present a number of existing analyses of past climatic records for California, the Sierra Nevada and Lake Tahoe that provide evidence for observed recent climatic trends.

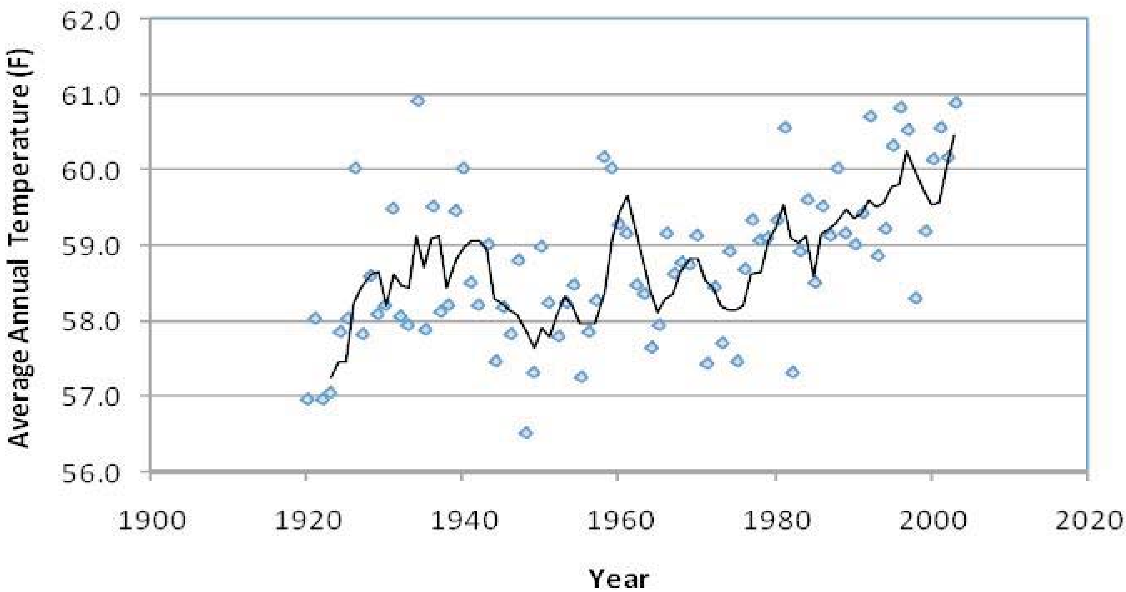
There are a number of available climate-related continuous datasets obtained throughout California and within the Lake Tahoe Basin. A long-term atmospheric monitoring network of six research buoys is maintained by researchers from the University of California, Tahoe Environmental Research Center (TERC) (http://remote.ucdavis.edu/tahoe_location.asp) and the NASA Jet Propulsion Laboratory has characterized baseline atmospheric conditions since 1999 (http://laketahoe.jpl.nasa.gov/get_met_weather). Another six meteorological stations maintained by TERC are located on land adjacent to the Lake (http://remote.ucdavis.edu/tahoe_location.asp) (Figure 3.1). NRCS administers 10 SNOTEL stations in the Lake Tahoe Basin, which have operated since the late 1970s and monitor precipitation, temperature, and snow depth (http://www.wcc.nrcs.usda.gov/snow/). The United States Geological Survey (USGS) has a wide array of surface water gauging stations on Lake Tahoe streams that were initiated as early as the 1900s and have continued at different intervals (http://waterdata.usgs.gov/nwis/rt) at different locations (see Figure 3.1) and provide an invaluable time series of local hydrologic observations. The Western Regional Climate Center (http://www.wrcc.dri.edu/) also provides a historic dataset of temperature and precipitation conditions, with climate data going as far back as the early 1900s at some locations. Additional historical weather data can be found at Weather Underground (www.wunderground.com), which synthesizes numerous weather stations monitored by both public and private organizations within the Lake Tahoe Basin.

3.2 AIR TEMPERATURE

Observational evidence around the globe shows that all continents and oceans are being affected by regional climate changes. The most concrete and consistent finding is the particularly high confidence of observed air temperature increases (IPCC, 2007). Temperature increases during recent decades have been measured throughout California and the Sierra Nevada region using both data collected at the surface as well as by satellite sensors (Coats et al. 2006; Schneider et al., 2009). The overall change in California annual temperatures is shown in Figure 3.2. California annual nighttime temperatures have increased by 0.33^{o}F per decade since 1920 and annual daytime temperatures have increased 0.1^{o}F per decade (Moser et al., 2009).



Locations of lake and meteorological monitoring stations maintained by the Tahoe Environmental Research Center (TERC) and USGS stream gauge stations. Source: TERC, 2009



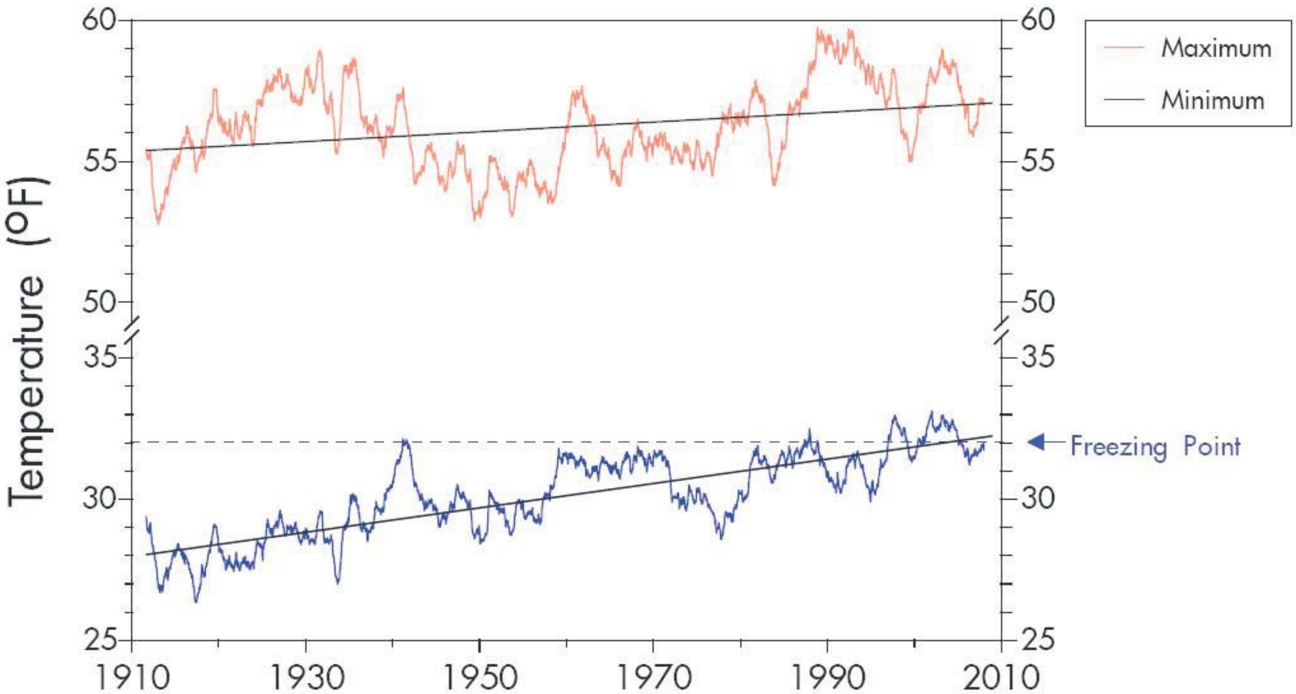
Historic air temperature for California. The solid black line denotes the upward trend of the five-year running average. Warming trends due to urabnization have been removed. Source: Moser et al., 2009

The recent history of surface-based temperatures collected at weather stations in the Lake Tahoe region show a strong upward trend in air temperatures that is consistent with global and regional changes (Coats et al., 2006). The observed warming is occurring primarily in spring and in the late in summer (Coats, 2010). Average daily temperature records in Tahoe City show an increase in the daily minimum temperatures by approximately 1.5^{o}F and nightly minimum temperatures have increased by more than 4^{o}F since 1910 (Figure 3.3). The historic temperature records show a high degree of variability from one year to the next, but a best fit line illustrates a decreasing trend in the number of days below freezing in the Lake Tahoe Basin over the past century, resulting in approximately 30 less days below the freezing point in 2000 than there were in 1910 (Figure 3.4).

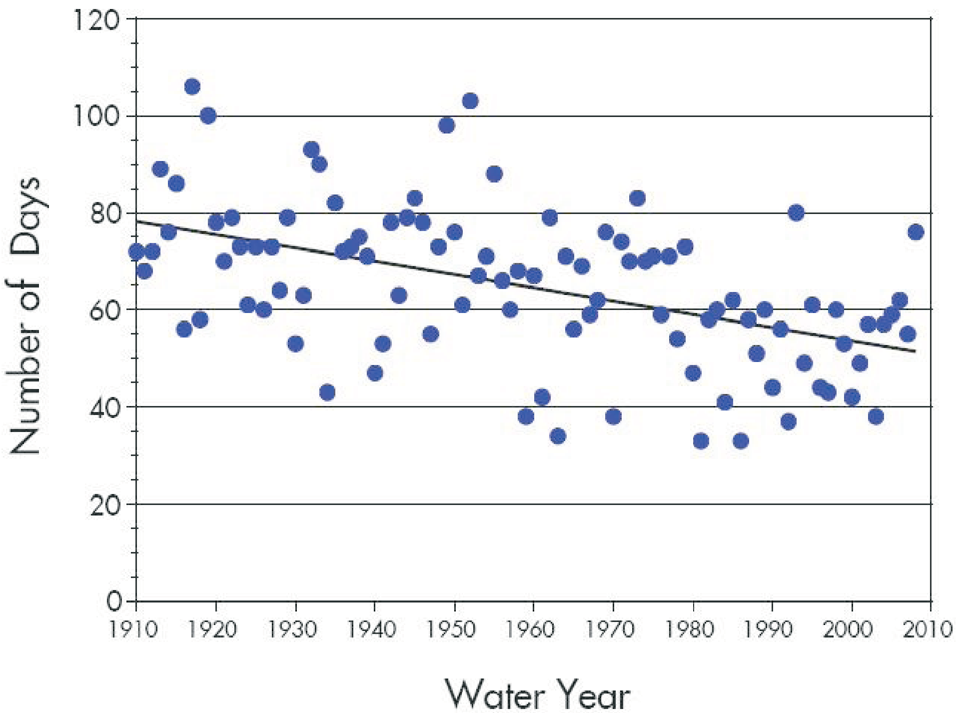
3.3 PRECIPITATION

Long-term trend analysis by Kapnick and Hall (2010) shows that since 1930 there has been a trend toward earlier snow mass peak timing of 0.4 days per decade, which is attributed to warming in the month of March in the Sierra Nevada (Figure 3.5). The majority of stations measured in the Sierra Nevada have experienced simultaneous reductions in April 1 snow water equivalent (SWE) that is attributable to earlier snowmelt rather than reductions in total snowfall (Kapnick and Hall 2010). SWE can be thought of as the depth of water that would theoretically result if the entire snowpack melted instantaneously. SWE indicates how much water is stored in the snowpack reservoir that can be slowly released as melt water during the spring and summer months. SWE is strongly dependent on concurrent precipitation changes and watershed topography (Howat and Tulaczyk, 2005). Lower elevations are more vulnerable to the effects of warming since a small rise in average temperature will create an earlier snowmelt or a shift in precipitation delivery from snow to precipitation (Figure 3.6). While some reduction in the April 1 SWE at low elevations is offset by increases in precipitation at higher elevations (Howat and Tulaczyk, 2005), recent work indicates a reduction in both April 1 SWE and spring runoff in the Sierra Nevada region during recent decades (Moser et al., 2009).

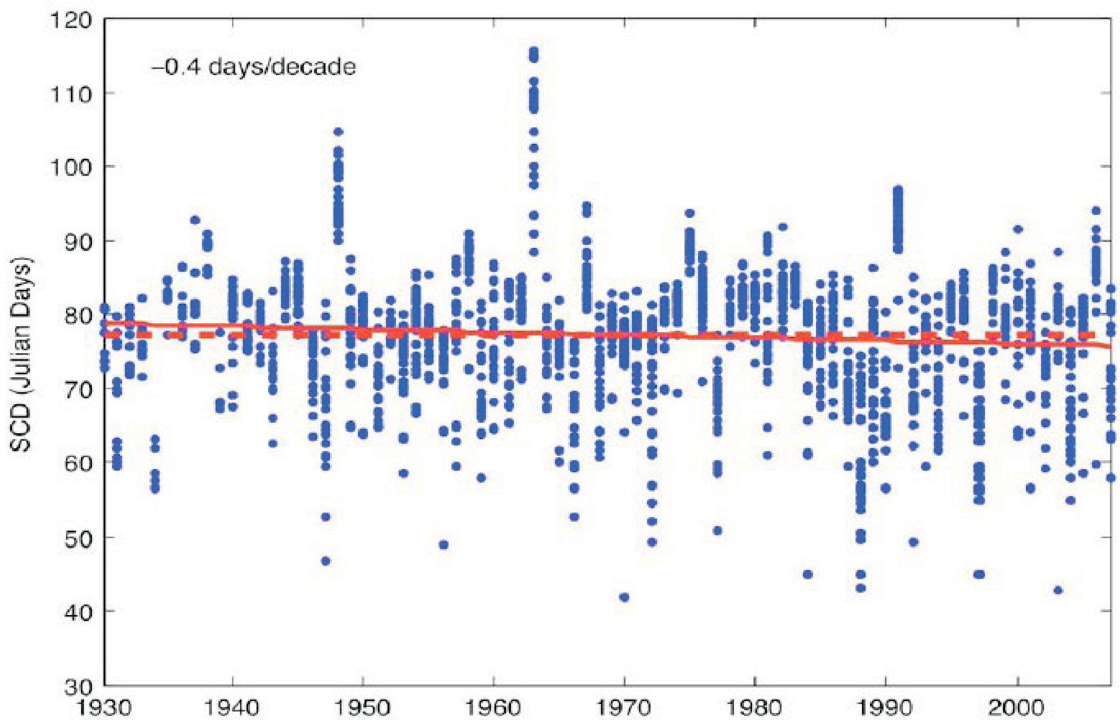
Total annual precipitation at Tahoe City shows high variability over the previous century. The minimum annual total over the previous century was 22.5 cm in 1977 and the maximum was 174 cm in 1982, and there is no clear trend either up or down over the past 100 years (TERC, 2009). While there are no readily identifiable trends in the total annual precipitation, changes in the character of the precipitation patterns are evident in data collected from 1910 to 2008, which show a shift from snow to rain, increased rainfall intensity, and increased inter-annual variability (Coats, 2010). In the Sierra Nevada region, warmer winter and spring temperatures are causing a decrease in the proportion of precipitation delivered as snow relative to rain (Dettinger and Cayan, 1995; Mote, 2003; Dettinger, 2005; Mote et al., 2005; Knowles et al., 2006). Historically, more than 50% of the annual precipitation totals in the Tahoe Basin are delivered as snow. The TERC analysis of historic precipitation records indicates an approximate 12% reduction in snowfall as a fraction of total precipitation from 52% in 1910 to 34% in 2009 (Figure 3.7). A similar trend towards a reduced snow/rain ratio is evidenced at the regional scale using data from National Climatic Data Center (Knowles et al., 2006). While the proportion and amount of snow vary substantially from year to year, less snow generally means a quicker depletion of the snow storage reservoir during the spring/summer season. This will increase the likelihood that that in a given year the local hydrologic system will not be sufficient during the dry months to maintain aquatic ecosystems or support the same magnitude of consumptive water uses in the future.



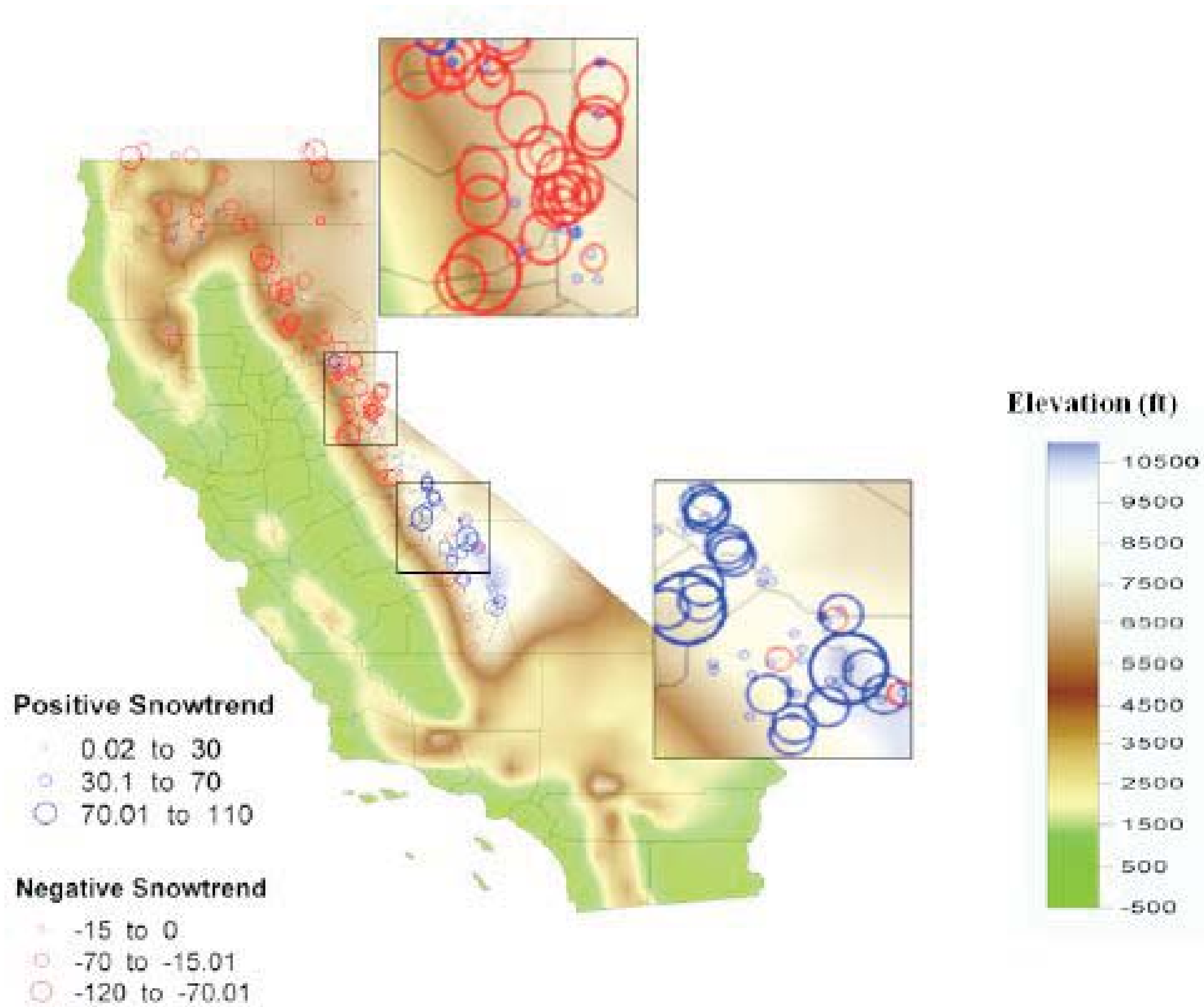
Daily air temperatures,1910-2009, from the UC Davis Tahoe Environmental Research Center meteorological stations. The red and blue lines are two-year moving averages for the maximum and minimum daily temperatures, respectively, with long-term trend lines included. Source TERC, 2009



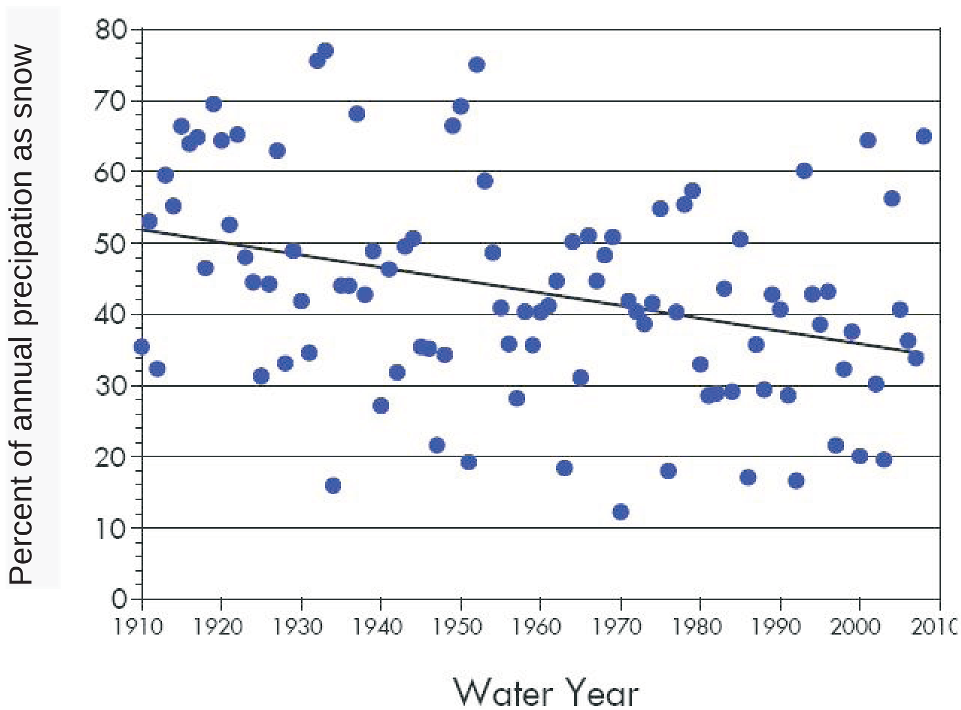
Number of days below freezing 1910-2009 from the UC Davis Tahoe Environmental Research Center meteorological stations. Data trend suggests a decline from nearly 80 days below freezing to less than 60 days per year by the end of the 20th century. Water years are October 1 to September 30. Source TERC, 2009



Peak snow mass for 27 Sierra Nevada stations from 1930 to 2007. The peak snow mass timing is defined as the temporal centroid date (SCD) for each year. The SCD equals the center of mass for snow water equivalent (SWE) values from February 1 to May 1 The dashed red line denotes the mean SCD and the solid red line denotes the decreasing trend in the spring day each year when the peak snow pack is present in the Sierra Nevada. Source: Kapnick and Hall, 2009



April 1 snow level trends 1950-1997. The red points indicate percent decrease in April 1 snow levels and blue points indicate percent increase. Source: Moser et al., 2009



Percent of annual precipitation delivered as snow from the UC Davis Tahoe Environmental Research Center meteorological stations. While there is a large degree of scatter, the data trend suggests a shift from over 50% to less than 40% of the annual preciptiation deivered as snow. Source: TERC. 2009

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TAHOE PERCENT OF ANNUAL PRECIPITATION AS SNOW, 1910-2009

FIGURE 3.7

3.4 HYDROLOGY

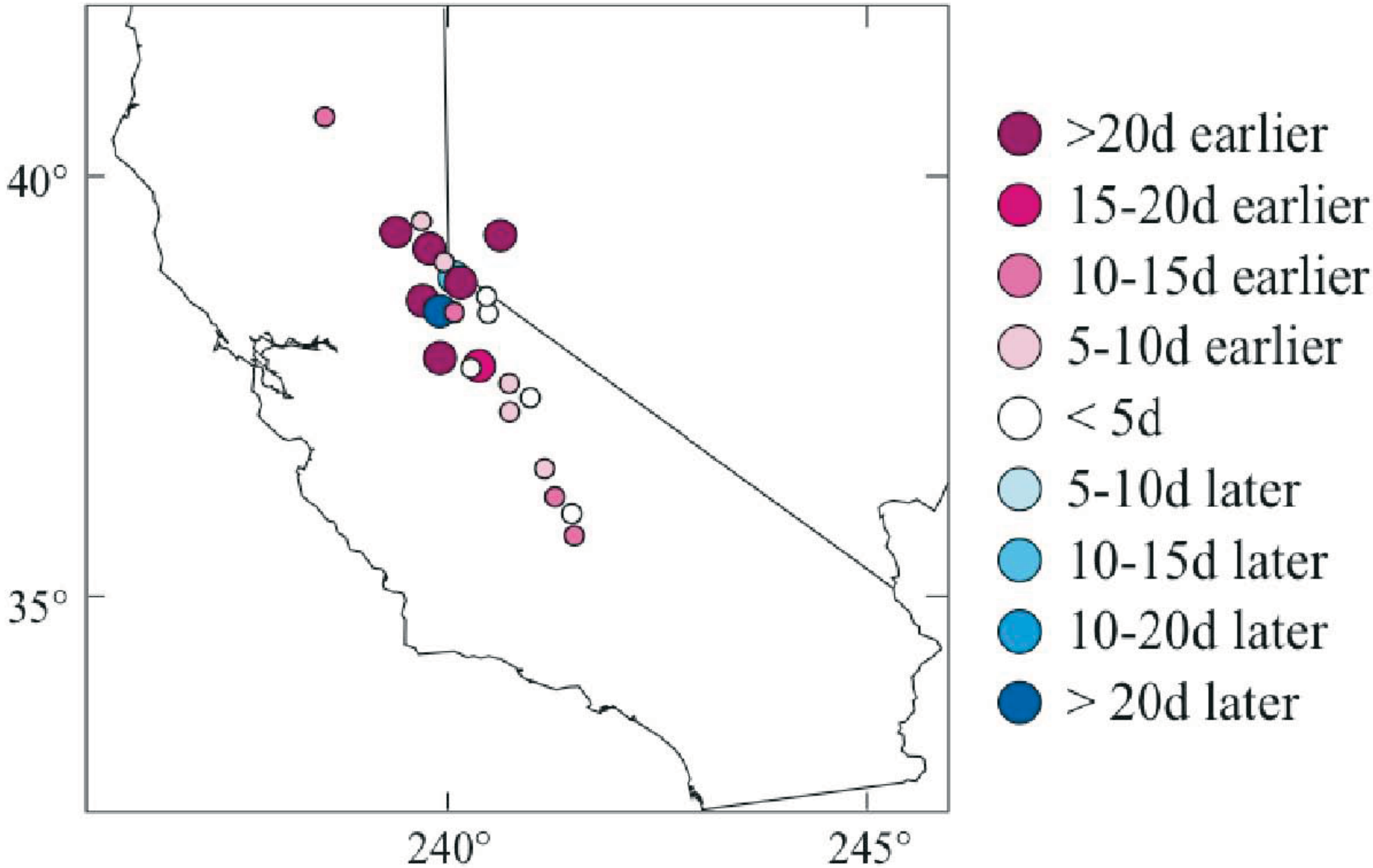
Watershed hydrologic processes, such as evapotranspiration, snowmelt, groundwater recharge, and flooding, are driven by atmospheric variables: primarily precipitation and temperature. Warming temperatures in the Sierra Nevada are causing increasingly earlier spring snowmelt runoff (Cayan et al. 2001; Stewart et al. 2005; Coats 2010a) and a diminishing snowpack volume. This seasonal change in the spring snowmelt is indicated by the long-term trend in the timing of the annual peak springtime stream flows. Daily river flows increase throughout spring as the snow melts because of rising air temperatures, increasing solar radiation and longer days. The observed recent shifts in the temperature and precipitation patterns in the Lake Tahoe Basin have resulted in reduced annual snow pack volume, earlier snowmelt stream discharge peak in the spring, and a reduced duration of snow pack persistence. However, no significant change in the amount of total annual precipitation has been observed in historic data.

Stewart et al. (2005) used statistical models to quantify trends toward earlier springtime snowmelt across North America. They showed that both the spring peak snowmelt and the spring pulse components of the hydrograph have been advancing earlier by 1-4 weeks in the year since the late 1940s with some of the most pronounced effects in the northern Sierra Nevada mountain basins. Most of the trends in snowmelt timing indicate that the initiation of the spring pulse occurred between 5-20 days earlier in 2002 than it did in 1948 (Figure 3.8; Peterson et al., 2008). The spring peak discharge timing is typically influenced more by air temperature than by the size of the initial snowpack (Peterson et al., 2008), thus the shift to an earlier spring melt is indicative of increased air temperature trends. Figure 3.9 shows that the timing of the peak flow on the Kern River (a snowmelt-influenced stream in Central California) has trended towards an earlier spring melt timing from 1960 to 2000. Several areas in the Sierra Nevada show statistically significant changes in the timing of the initiation of the spring pulse. Daily streamflow data for gauging stations in and around the Tahoe Basin show a shift in snowmelt timing to earlier dates. Coats (2010a) reported statistically significant shifts in the date of peak snowmelt discharge for a number of watersheds in the Tahoe Basin (Figure 3.10). Peak flow timing from the 1960s and early 1970s to 2005 showed significant shifts in the Upper Truckee River ($p<0.05$), Trout Creek ($p<0.05$), Ward Creek ($p<0.10$) and Blackwood Creek ($p<0.10$) with slopes ranging from -0.205 to -0.465 days/year (see figure 3.10).

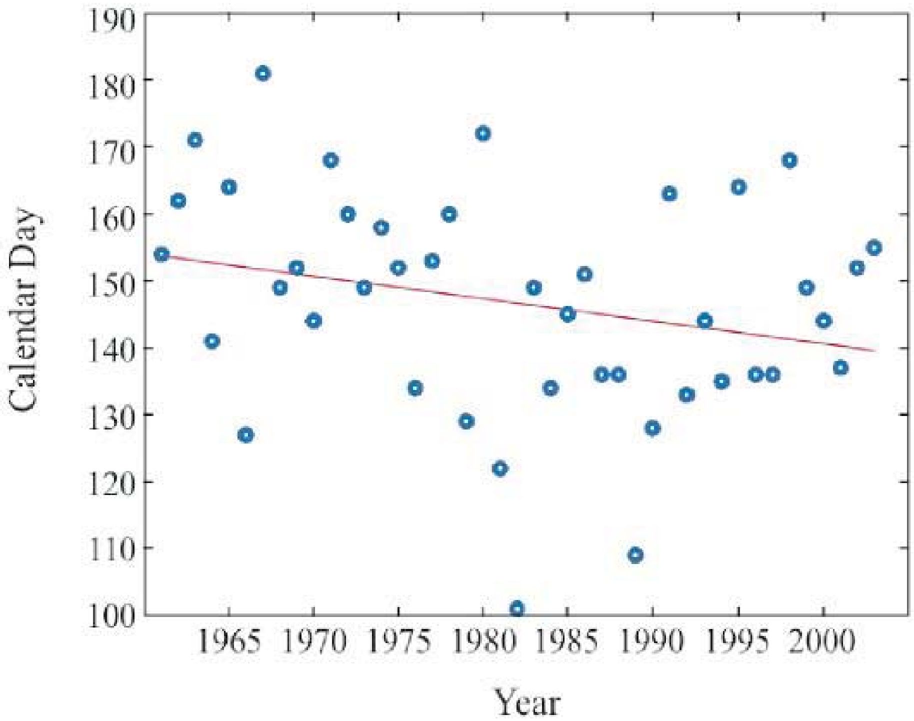
The high degree of natural variability usually present in long-term hydrologic data presents scientists with a substantial challenge in detecting the signal of a change above the 'noise' in the system with a high level of confidence. Using Figure 3.11 as an example, the best fit linear regression through the day of the Upper Truckee River peak snowmelt discharge record from the 1960s to 2007 indicates the average peak now occurs 17.5 days earlier than it did in 1961. The slope of the best-fit line suggests the timing of spring snowmelt peak is estimated to progress earlier by an average rate of 0.42 days/yr (TERC, 2009). While the best-fit line provides these general trends, the scatter and standard deviation of the data within Figure 3.11 is substantial. At the time that this synthesis was drafted in the summer of 2010, the peak snowmelt on the Upper Truckee River occurred on June 8, actually later than the average date of the snowmelt peak observed during the 1960s.

3.5 LAKE TAHOE TEMPERATURE AND DYNAMICS

There is a high level of confidence associated with the warming of lakes and rivers around the world (IPCC, 2007), affecting thermal structure and water quality (Schneider et al., 2009). The characterization of temperature change over land is primarily based on measurements at meteorological stations (Hansen et al., 2006). Lakes act as



Trends (1948–2002) in snowmelt discharge timing, based on the start of the spring pulse. A 15 to 20 day earlier trend means the linear trend estimate in the timing of the spring pulse starting in 1948 was 15 to 20 days earlier than in 2002. Large circles represent statistically significant trends (95% confidence level) and small circles are not statistically significant. Source: Peterson et al., 2008



Calendar day when the peak daily discharge occured on the Kern River, CA, illustrating significant inter-annual variability and a general trend towards earlier annual peak discharge since the 1960's. Source: Petersen et al., 2008

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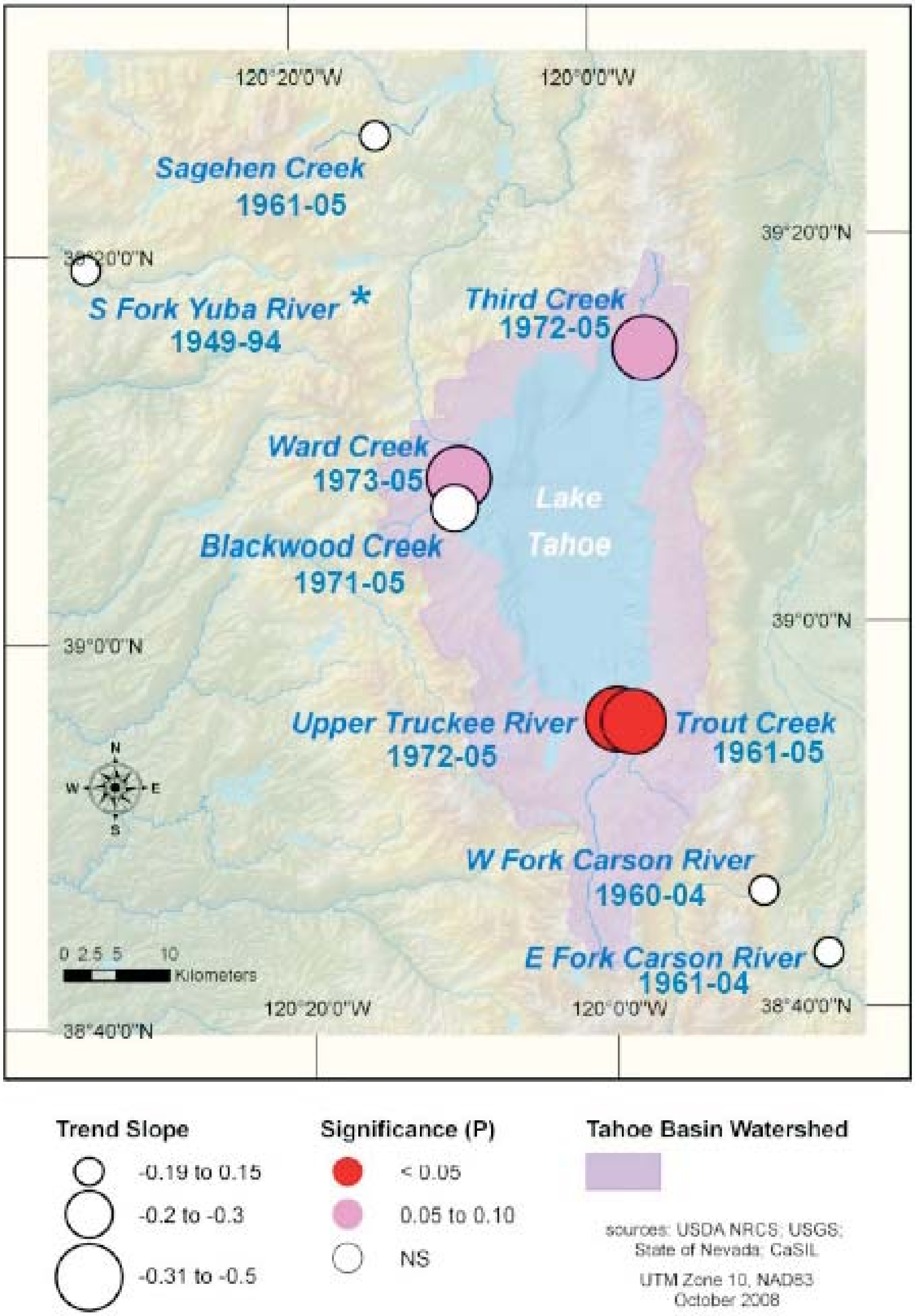
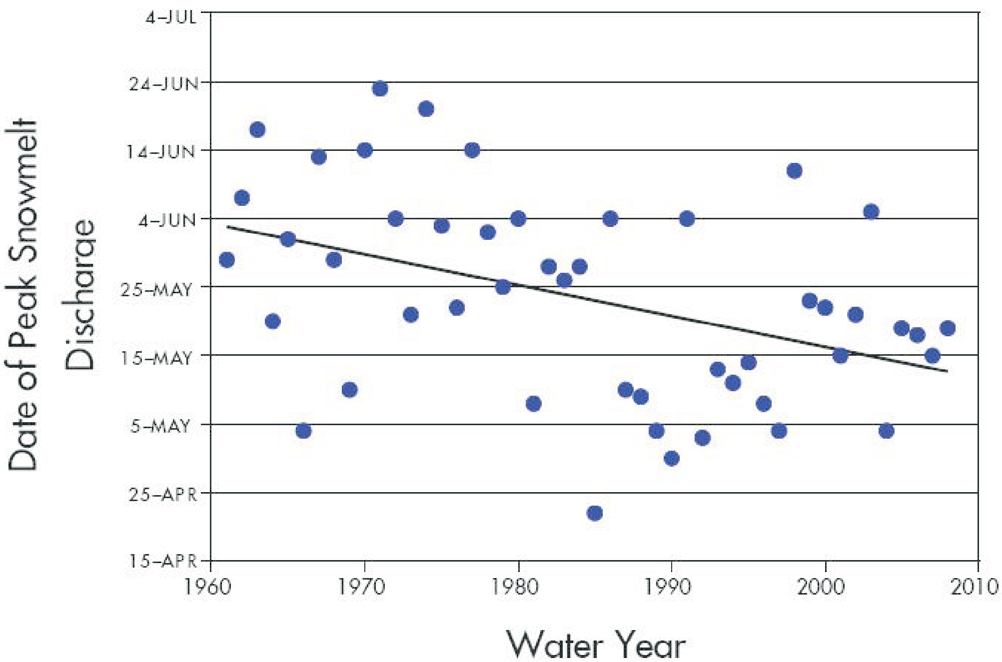


Shift in the date of peak snowmelt discharge for streams in and near the Tahoe Basin. The pink and red dots indicate streams with shifts of peak snowmelt discharge significant at the 95% confidence level. Trend slope (days/yr) and significance (corrected for autocorrelation) from Kendall Trend Test (1960-2004). Effect of total annual snowfall (1961-2004) removed by LOWESS smoothing. Map by Janet Brewster, CTC presented by Coats, 2010

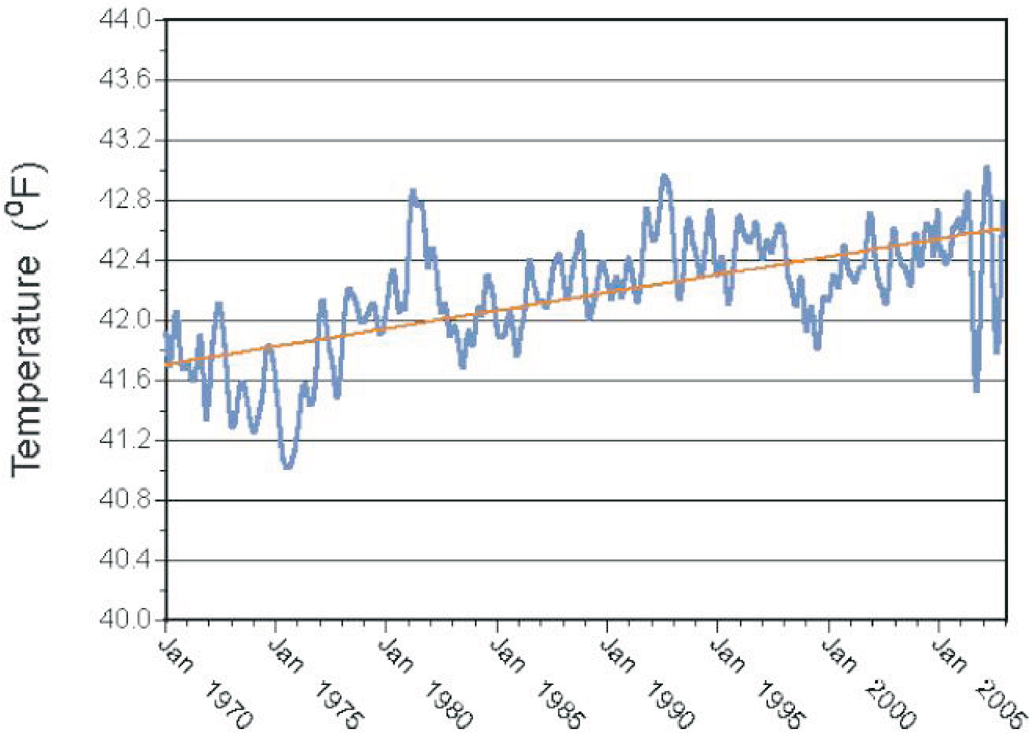


The date of peak snowmelt discharge for the Upper Truckee River, measured as the date of maximum daily streamflow for each water year (October 1 to September 30) from 1961-2007. The best fit linear regression suggests a trend toward earlier snowmelt on average; however 2010 UTR peak discharge occured in mid June, later than the 1960 peak as predicted by the linear regression. Source: TERC, 2009 integrators of atmospheric influences on temperature. Their high heat capacity dampens short-term temperature variability, highlighting long-term variations in temperature (Schneider et al. 2009). Therefore, long-term lake temperature patterns can be good indicators of climate change. Thermal infrared satellite imagery has been used to show that the surface waters of lakes in the Sierra Nevada region have been warming at a rate of 0.11^{o}C/yr since 1992 and that this pace of warming is approximately twice as fast as the increase in average minimum surface air temperature (Schneider et al., 2009).

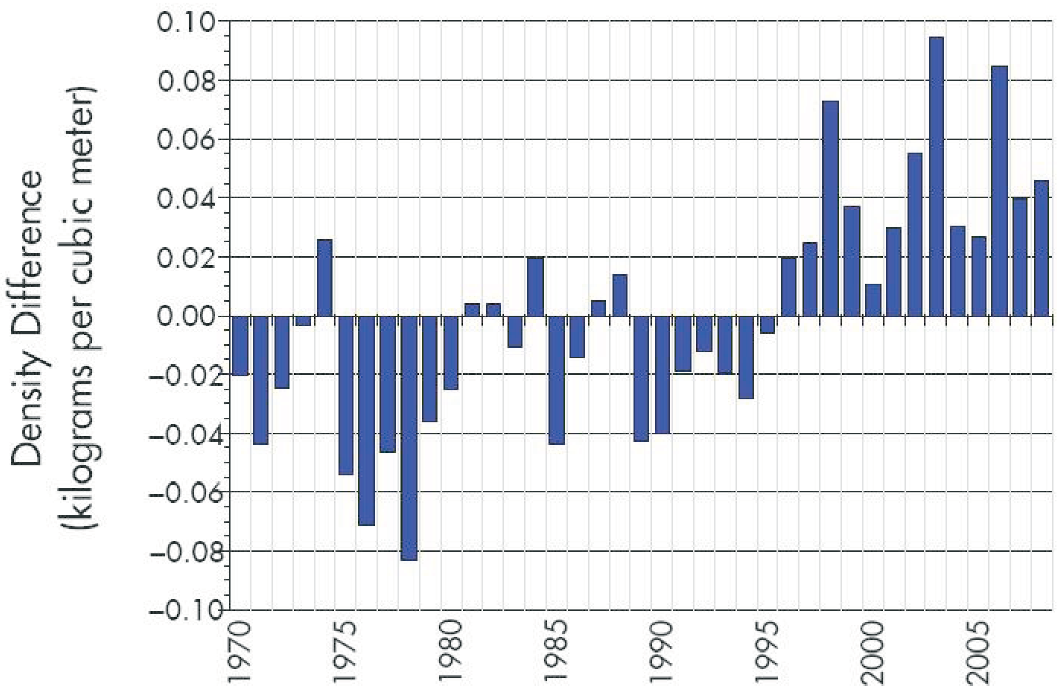
Data from the TERC monitoring network shows that Lake Tahoe reflects regional trends. The average daily surface temperatures rose 0.8^{o}C, from 10.1^{o}C in 1968 to 10.9^{o}C in 2008, and the volume-averaged temperatures have changed by 0.5 ^{o}C, from 5.4 ^{o}C in 1970 to 5.9 ^{o}C in 2008 (Figure 3.12). Coats et al. (2006) found that the volume-weighted mean temperature of Lake Tahoe is increasing at a rate of 0.015 ^{o}C/yr with the highest rate of warming at the surface of the lake. The upward trend in surface water temperatures changes the thermal structure of Lake Tahoe (Coats et al., 2006).

The depth and stability of the vertical temperature differences (i.e., thermal stratification) and wind influence the mixing depth of lakes. During the warm summer months the surface waters are relatively warmer than the bottom waters, resulting in a thermal stratification. The thermal gradient acts as a chemical barrier preventing free exchange between the surface and bottom waters for dissolved oxygen and dissolved nutrients. During the winter months the surface waters cool and the vertical temperature of Lake Tahoe becomes uniform, eliminating the vertical stratification barrier. During years when the surface waters become colder than the bottom waters, the denser cold waters sink and the Lake completely mixes or “turns over”. This annual exchange maintains the vertical chemical balance of Lake Tahoe, as we know it today, bringing nutrients to the surface where they promote algae growth and, more importantly, periodically oxygenating the deep waters on regular intervals.

The deepest level of mixing varies from year to year and generally occurs in late February to early March, and according to historic records, Lake Tahoe turns over an average of 1 time every 4 years. TERC monitoring data demonstrate that persistence of thermal stratification within the lake has increased since 1970 (Figure 3.13) and that complete mixing of Lake Tahoe during two or more successive years has only occurred three times since 1973 (TERC, 2009). The warming of Lake Tahoe’s surface waters and an increase in the annual minimum surface water temperature will reduce the frequency of these mixing events and affect limnologic function (discussed in Chapter 6).



Volume-averaged water temperature of Lake Tahoe over time. These data have been smoothed and filtered to remove the effects of seasonality and illustrate a long-term warming trend. Source: Coats, 2010



Lake Tahoe average annual surface water and deep water temperatures differences, converted to density. Each bar represents the annual average density difference between deep (100 to 165 feet) and shallow (0 to 33 feet) water, subtracted from the mean density for Lake Tahoe. Recently, density stratification of the lake has increased, which reduces the vertical exchange of water within Lake Tahoe. Source: TERC, 2009

CHAPTER 4 - CLIMATE CHANGE PROJECTIONS FOR LAKE TAHOE REGION

Global climate model outputs have been downscaled to project changes for the State of California, Sierra Nevada, and the Lake Tahoe Basin. Among these projections, there is consistent agreement of an increase in air temperatures into the future for California, but the magnitude is strongly dependent upon the emissions scenario and model used. Generally, research provides mixed results on the future of California annual precipitation totals. Some models predict increases in total precipitation in Northern California and drier conditions in Southern California. Other models predict no discernible change in the total Northern California precipitation by 2100. The likelihood of a continued reduction in winter snow totals with a concurrent increase in winter rains are predicted across the Sierra Nevada region (CNRA, 2009). The effects of extreme weather events will be measurable before those of the long-term trends, because the events occur over short timescales (days to years) as opposed to effects that occur over longer periods of time (decades). While the projected long-term shifts in the climate system will have important consequences, the resulting impacts will take comparatively longer to quantify and are too subtle for the public to notice. Table 4.1 summarizes the general expected climatic trends expected for the Lake Tahoe Basin over the next century and the content is supported by the existing research and available information on climate change as presented in Chapter 4. The relative confidence in the direction of the expected climate variable and seasonal patterns is also provided on a 1-5 scale as defined in Chapter 2.

Climate variable	Spatial context	Direction of expected change	Magnitude of expected change and time period	Seasonal patterns	Confidence ranking
Average air temperatures	Lake Tahoe Basin	Increase	1.5 to 5°C increase by 2100 [17]	Increase in annual average maximums (summer); Increase in annual average minimums (winter); Increase in average annual temps.	High
Extreme temperature events	California	Increase	5.6 to 11.1 °C increase in 100-yr. 3-day mean max. temperature [55]	More frequent heat waves and hot days (summer); Less frequent freezing spells (winter)	High
Precipitation totals	California	Slight decrease	No change to 20% decrease by 2100 [14]	Increases in winter; Decreases in summer and spring; Less frequent precipitation events	Low
Extreme precipitation events	California	Increase	Moderate tendency for increase in frequency and magnitude [12]	Increased frequency and high precipitation events in winter	Moderate
% of precipitation as snow	Lake Tahoe Basin	Decrease	17-22% increase by 2100 [17]	Increase in winter air temperatures will increase likelihood of more precipitation falling as rain.	Moderate
Rain on snow events	Lake Tahoe Basin	Increase	-	Increase in winter air temperatures will increase likelihood of more frequent rain on snow events.	Moderate

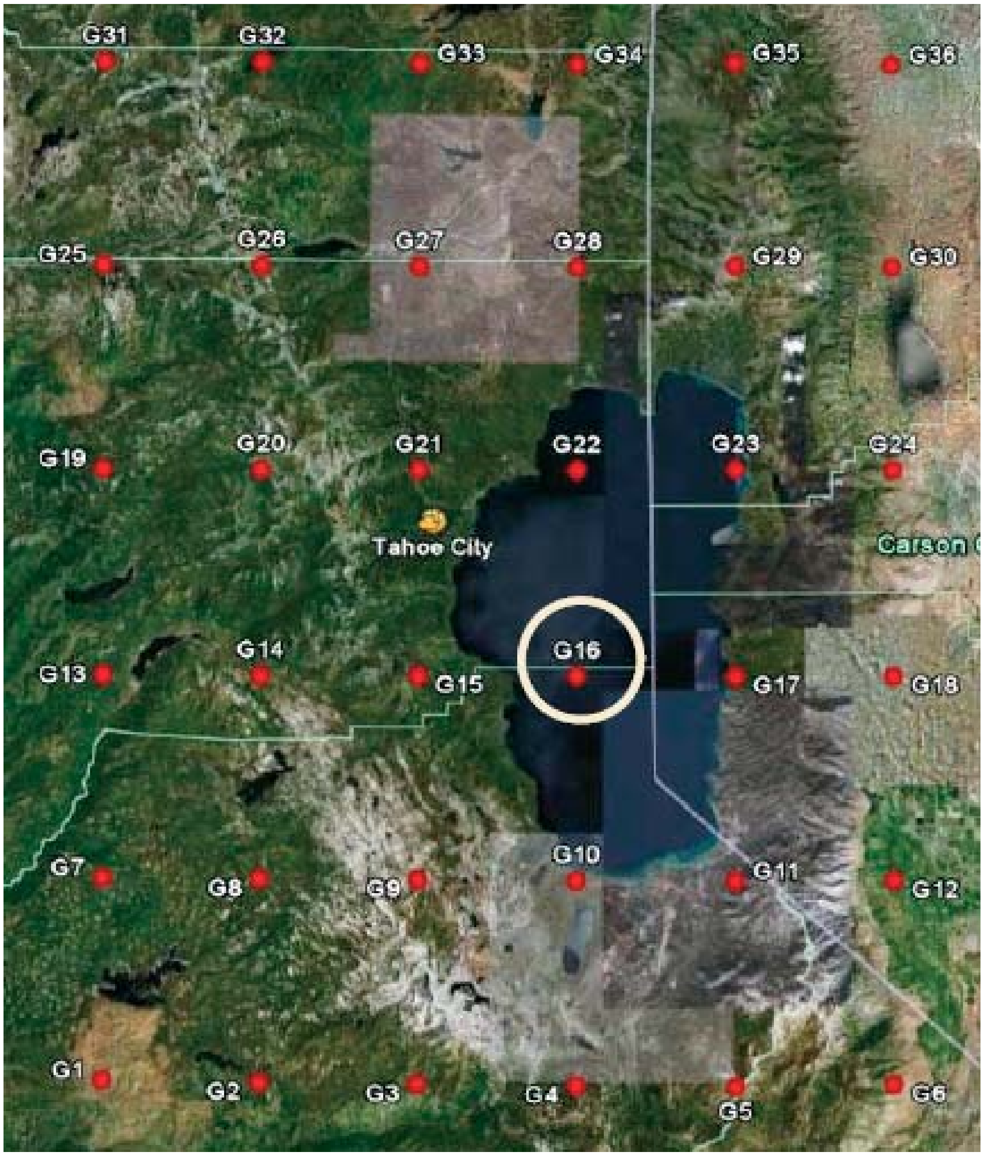
Table 4.1. Lake Tahoe Basin climate change summary. *Note: footnotes refer to literature cited in Chapter 8 – References, listed in alphabetical and numerical order.*

4.1 AIR TEMPERATURE PROJECTIONS

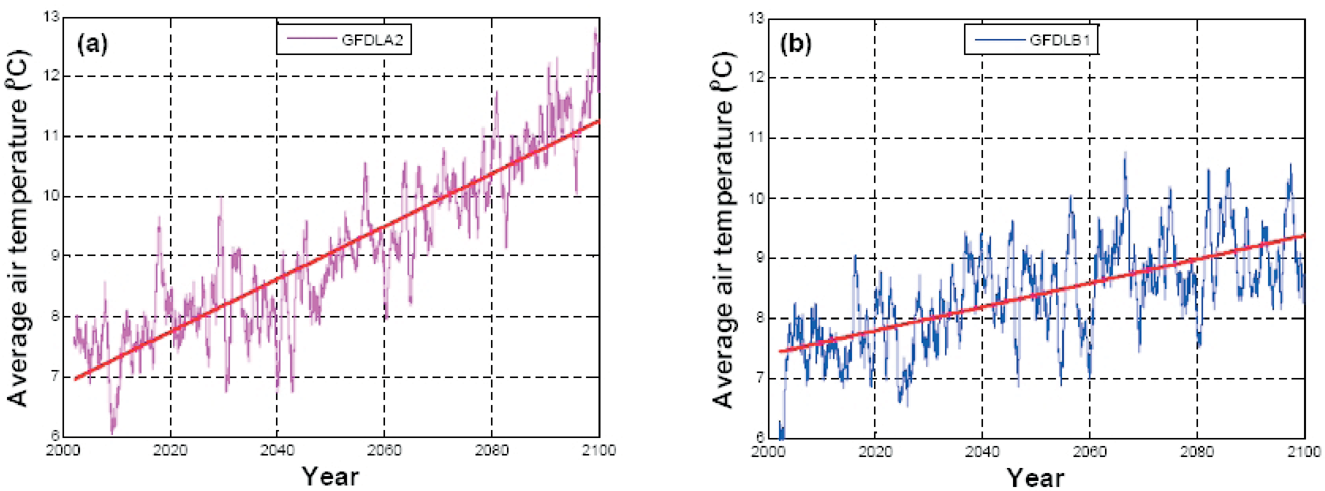
A number of climatic modeling studies suggest that air temperatures within the Lake Tahoe Basin will increase substantially during the 21st century. Projections for Lake Tahoe Basin climate are based on downscaling output from the GFDL and PCM for the A2 and B1 scenarios (Hidalgo et al., 2008) to 7.5' grid cells centered on Lake Tahoe (Figure 4.1). Coats et al. (2010) projected average air temperature increases between 2000 and 2100 were approximately 1.9 °C under the B1 scenario and 3.2 °C under the A2 scenario (Figure 4.2). Coats et al. (2010) used an average of 12 downscaled grid points surrounding the Lake Tahoe region and the same two climate models to estimate approximately 1.5°C to 5°C increases by 2100 for both maximum and minimum average annual temperatures.

Projected air temperature changes in the Lake Tahoe Basin over the next century fall within the range of projections for California overall (which are more developed and widely available in the literature). While a significant range exists in the magnitude and pattern of the projections for California, a consistent warming trend is projected throughout the century regardless of the model or the emissions scenario. The 2008 California Climate Change Scenarios Assessment simulation results exhibit warming across California and retention of the familiar Mediterranean seasonal pattern, with warm summers and mild wet winters (Cayan et al., 2009). A comparison of the six models used in the 2008 Scenarios Assessment (see Table 2.2) using both the A2 and B1 emissions scenarios produce a range of warming projections for California. The Scenarios Assessment predicted an increase in the average annual air temperature of 1°C to 3°C by 2060 by the B1 and A2 scenarios respectively. By 2090 the average annual California air temperature is predicted to increase from 2°C (B1) to 5°C (A2) (Cayan, et al., 2009). These projections have a greater temperature range compared to previous modeling results downscaled for California from Hayhoe et al. (2004). Again, it should be noted that the B1 emissions scenario is considered an optimistic future global emissions conditions that would require significant technological and industrial changes worldwide.

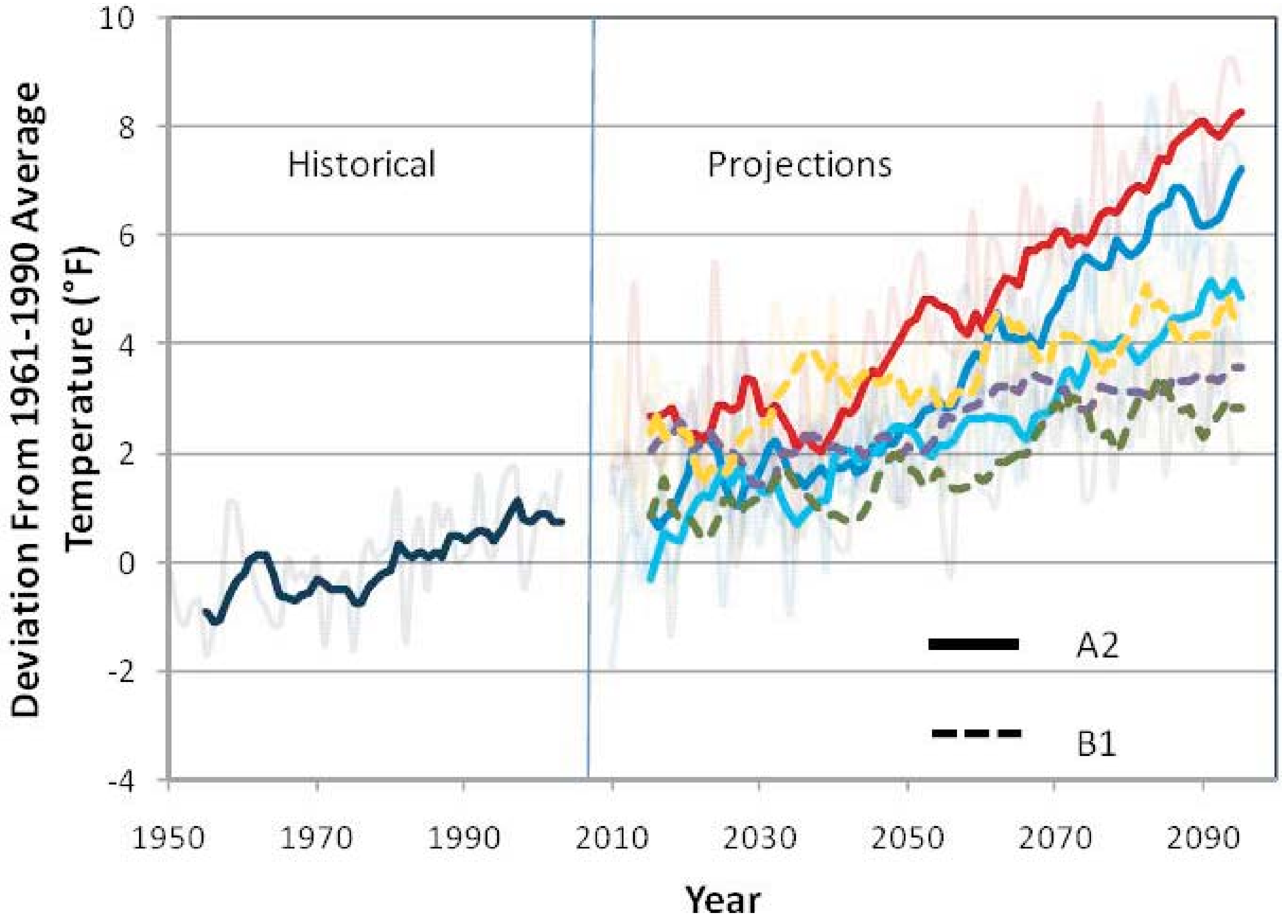
Moser et al. (2009) utilized three different global climate models and the A2 and B1 emissions scenarios to estimate the future average annual air temperature for California (Figure 4.3). While the absolute magnitude of California air temperature increase by 2100 and even the decadal patterns vary for each scenario and model combination, all outputs predict a substantial increase in average air temperature over the next century. Climate models also suggest the future warming trends may not occur equally across seasons within California; many model simulations indicate a disproportionate amount of the warming will occur during the spring months (Cayan et al., 2009). Figure 4.4 shows average spring temperatures for the historical and projected 21st century periods under the A2 scenario. The results indicate that future projections of average spring temperatures in California exceed the 90th percentile maximum temperature (8.4°C) much more frequently in the 21st century compared to the historical period of record.



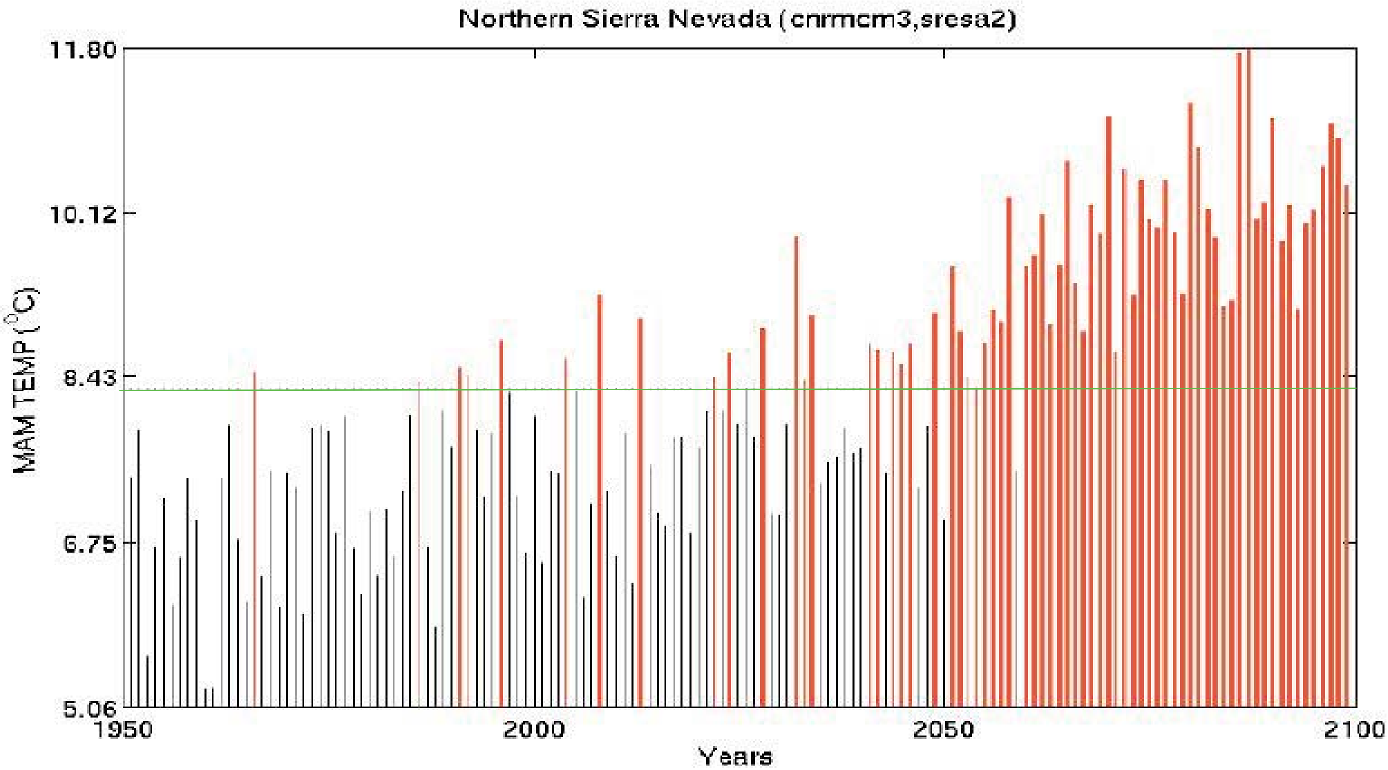
The image shows the locations of grid cell centers for data downscaled for use in Lake Tahoe climate estimates using GFDL model. The grid cell used to drive the climatic models (G16) is circled. Source: Coat et al., 2010



Air temperature projections for the 21st century in the Lake Tahoe Basin from the GFDL model under the A2 (left) and B1 (right) scenarios. Air temperature increases are consistently predicted over a wide range of GCM models as well as emission scenarios. Source: Coats et al., 2010



Historical and projected annual average temperatures for California for A2 (solid) and B1 (dashed) emissions scenarios. The soft lines represent annual average temperatures and the thick lines are the smoothed time series of annual average temperatures using a 6-year moving average. Notice the signficiant variation in the predictions from a range of models for both A2 and B1 emissions scenarios, yet all predictions expect an increase in future air temperatures. Source: Moser et al., 2009



Spring average temperature (ºC) for the Sacramento area from the CNRM A2 simulation for the historical and projected twenty-first century climate change periods. Years exceeding historical 90th percentile level (1961–1990) (which is denoted by the green horizontal line) are shown as red vertical bars. Source: Cayan et al., 2009

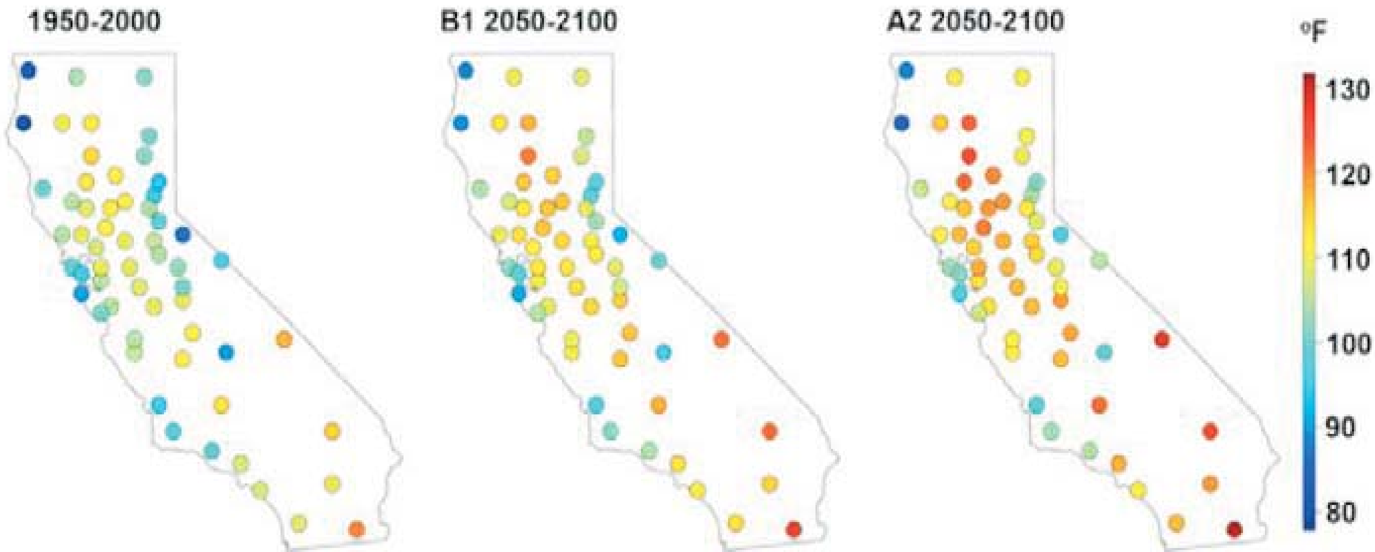
Indicators of temperature extremes from the climate models consistently predict a reduction in the number days when minimum daily temperatures will be below freezing, an increase in the number and duration of heat waves (Hayhoe et al., 2004; Gershunov and Douville, 2008; Miller et al., 2008), and an increase in summer nighttime minimum temperatures (Cayan et al., 2008; Mastrandrea et al., 2009) throughout California. Growing seasons and hot spell durations will lengthen and the frequency and magnitude of minimum nighttime temperatures are expected to increase (Mastrandrea et al., 2009). Heat waves of greater strength and intensity are likely to become more frequent all across the state, with some simulations suggesting that they will become an annual event by the end of this century under a higher emissions scenario such as A2. Freezing spells (defined as seven days or more when daily minimum temperatures are below 0^{o} C) are projected to become less frequent across the state, even in locations such as the Central Valley and Sierra Nevada where sustained freezing periods are not necessarily uncommon. Freezing spells are projected to become as rare as a one in ten-year event or less in most of California (Mastrandrea et al., 2009). Summers that fall in to the coolest third of historical data will be effectively eliminated based on projections from the GDFL model (Cayan et al., 2008b). Model simulations near Sacramento indicate a tripling of the frequency and substantial increase in intensity of hot days (Cayan et al., 2009).

Climate model outputs can also be expressed spatially and temporally as the relative expected frequency of occurrence. Figure 4.5 summarizes the projected changes in the 100-yr expected annual maximum 3-day mean for California by county. (The 100-year return interval temperature is the value that has a 1% chance of occurrence in any one year.) The image on the left in Figure 4.5 illustrates the historic observed values, reflecting the historic occurrence of relative rare heat wave events throughout California. The projected (2050-2100) magnitude of the same variable given the B1 emission scenario is presented in the middle map, and the A2 projections are displayed in the map on the right. The location nearest Lake Tahoe shows a change of approximately 10 ^{o}F (5.6 ^{o}C) under B1 and 20 ^{o}F (11.1 ^{o}C) under A2 (see Figure 4.5) from historical observations. In most areas of the state, projections indicate that the three-day mean maximum temperature that currently has a return period of 100 years will have a return period of less than 10 years in the future. This means that the hottest three day average temperature that right now is likely to occur once every 100 years, or has a 1% probability of occurring during any one year, will have a 10% probability of occurrence by 2100.

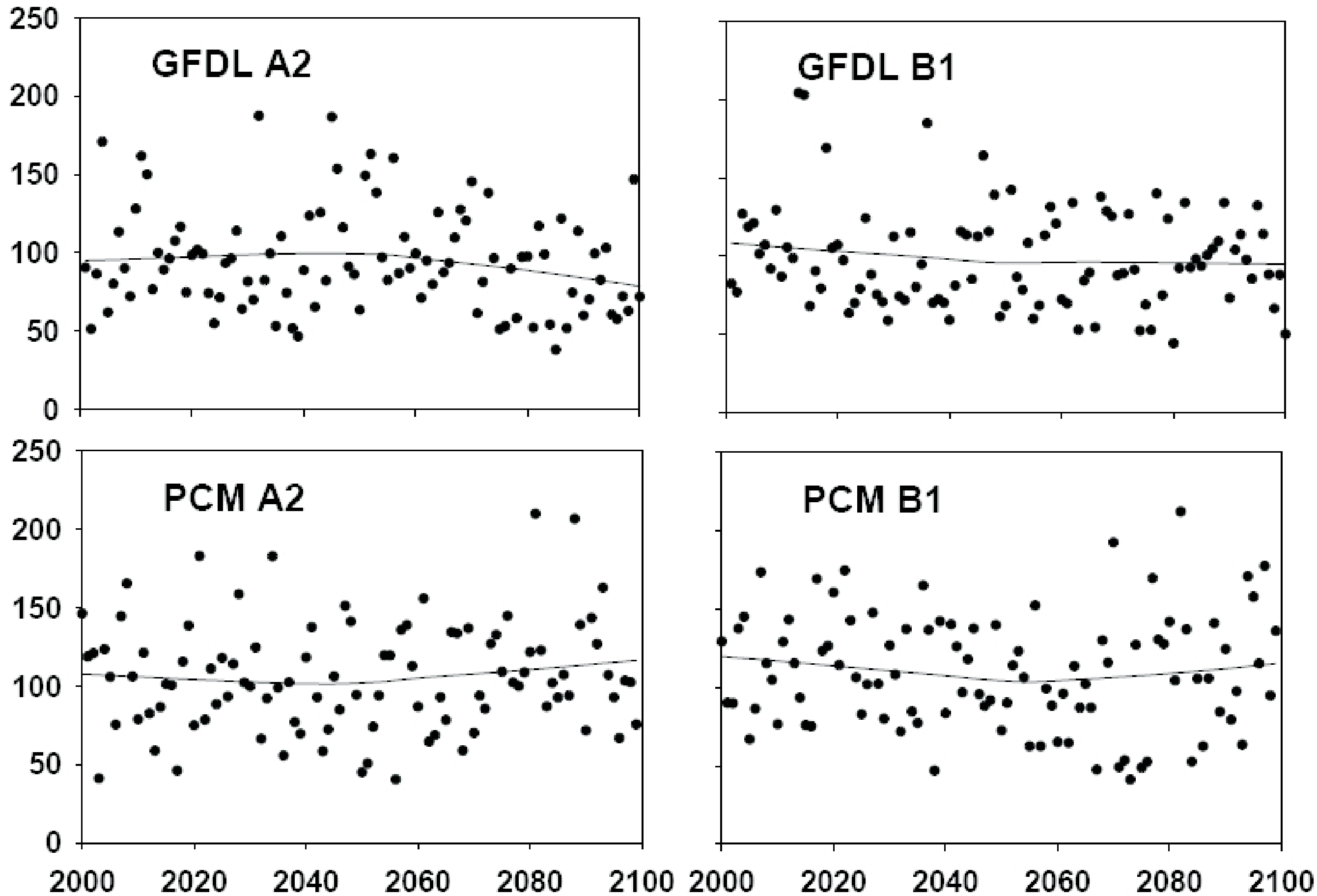
4.2 PRECIPITATION PROJECTIONS

Compared with air temperature trends, there is less consistency in the model predictions of future precipitation conditions in California, the Sierra Nevada, and the Lake Tahoe Basin, regardless of the emissions scenario (e.g., Maurer 2007). Thus, there is little confidence in the future response of average annual precipitation patterns as a result of climate change. The most confident expected precipitation response is a shift in the form of precipitation in the Sierra Nevada from less snow to more rain, based on the projected increase in air temperatures noted above.

Recent modeling studies using GCM projections downscaled to the Lake Tahoe Basin illustrate the weak and indiscernible trends in average annual precipitation into the 21st century. Projections from Coats et al. (2010) indicate a high degree of variability in precipitation projections over time with a very weak linear increase in annual precipitation totals under both A2 and B1 scenarios using the GFDL model. Figure 4.6 shows projected changes up to the year 2100 for the four combinations of models and scenarios presented by Coats (2010b), and the non-linear model fit have opposite inflection points around the year 2050. Precipitation projections completed by Coats (2010b) indicate a similar degree of variability in average annual precipitation using the GFDL and PCM models under the same two emissions scenarios (A2 and B1), which makes the expected change in average annual precipitation expected in the Lake Tahoe Basin over time difficult to discern with any confidence.



Simulated California 100-year return levels for three-day maximum temperatures, 1950–1999 and 2050–2099, by county using BCSD downscaling of ensemble averages from three global climate models. From left to right, maps present historical observations (1950-1999), projections (2050-2099) under the B1 scenario and the A2 scenario, respectively. Changes from cooler to warmer colors left to right indicate an increase in the three-day maximum temperature likely to occur during 100 years (1% probability in any given year). The figure shows that the location closest to Lake Tahoe shows an increase of about 20°F by 2100 under the A2 emissions scenario relative to the historic 3-day maximum. Source: modified from Mastrandrea et al., 2009



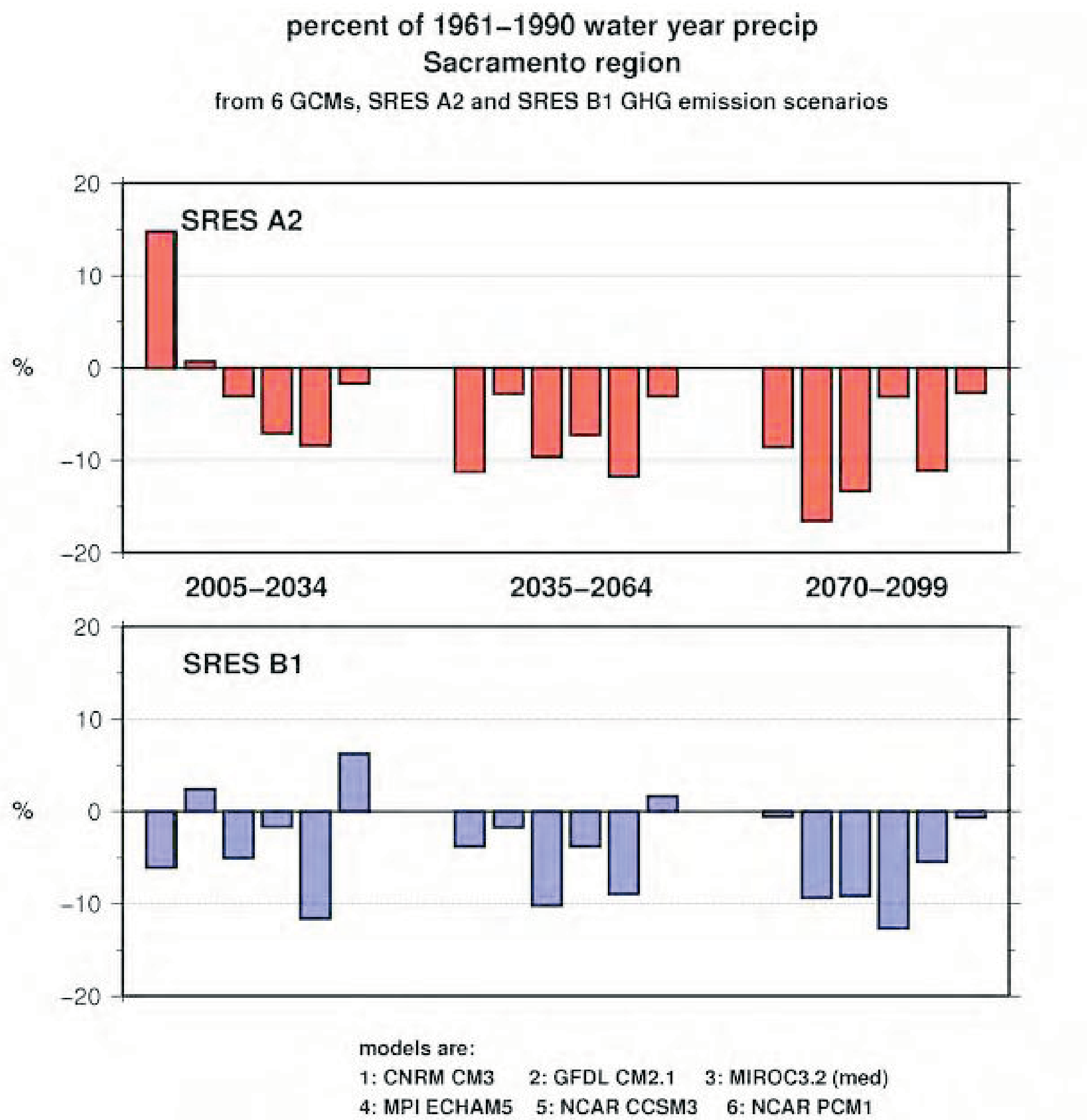
Lake Tahoe Basin precipitation projections for the GFDL and PCM climate models under the A2 and B1 scenarios. Source: Coats et al., 2010

The local Lake Tahoe Basin findings of high inter-annual variability and very slight changes (which are in all likelihood less than the level of uncertainty) in total annual precipitation during the 21st century agree with other modeling results at California regional and statewide spatial scales. Analysis of California-wide precipitation changes produced under B1 and A2 emissions scenarios using 11 global climate models by Maurer (2007) found only slight changes in mean annual precipitation, with some increases in precipitation in winter months and decreases in spring months. Similarly, Hayhoe et al. (2004) found slight precipitation decreases in the second half of the century with no obvious inter-scenario differences in magnitude or frequency of precipitation events. Experiments from the 2006 Scenarios Assessment indicated weak trends in mean annual precipitation from 2000-2100 for Northern California and a modest tendency for increases in the number and magnitudes of large precipitation events (Cayan et al., 2008b). These simulations showed slight or no change using one model (PCM) and 10-20% decrease in the mean annual precipitation totals using another model (GFDL) (Cayan et al., 2008b). Simulations completed by Mastrandrea et al. (2009) detected no significant changes in precipitation and showed inconsistent behavior when comparing results from different models and downscaling methods. Inconsistencies between downscaling approaches included the length of dry spells and trends in precipitation intensity (Mastrandrea et al., 2009).

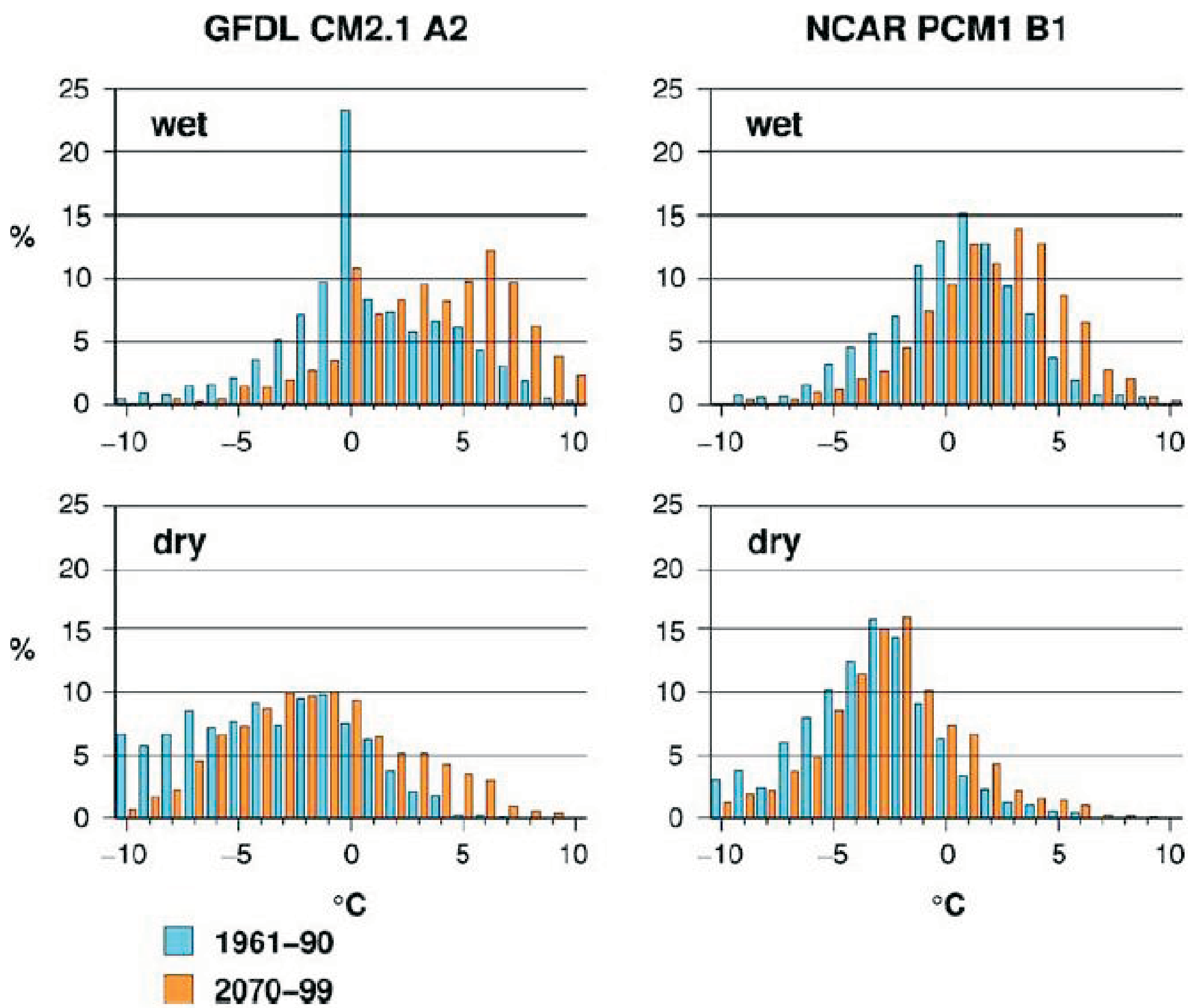
The most recent research from the Scenarios Assessment project reports a reduction in the average annual precipitation totals over the course of the next century for the Sacramento area, which has a strong correlation to precipitation of the Sierra Nevada watersheds (Cayan et al., 2009). In these simulations, all but one of the six climate models used showed declining trends in 30-year average precipitation totals for the Sacramento area relative to the 1961-1990 historical average under the A2 scenario (Figure 4.7) (Cayan et al., 2009). The model simulations under the B1 scenario predicted a relatively lower reduction in precipitation totals than the models under the A2 scenario, yet the majority of deviations ranged from 3% to less than 10% reductions relative to the historic observations. The authors suggested the analysis of daily model outputs indicates that the drying is associated with the decline in the frequency of precipitation events, rather than a decline in their intensity. Three of the models predicted reductions in the number of 3mm and greater precipitations events (Cayan et al., 2009). The characteristic high degree of variability in precipitation from month to month and from year to year also is expected to continue and California will retain its Mediterranean climate with relatively cool and wet winters and hot, dry summers (Cayan et al., 2008b; Cayan et al., 2009).

While trends in the overall amounts of precipitation appear to be moderate and the projections across models less consistent, there is good correspondence at different spatial scales that suggest that higher elevations in California will experience a shift towards more precipitation delivered as rain versus snow as a result of warmer temperatures (Hayhoe et al., 2004; Knowles et al., 2006). Simulations using GDFL and PCM models for Northern California predict substantial changes in the relative distributions of temperature and precipitation with both A2 and B1 scenarios (Figure 4.8). There is a notable shift in the frequency distribution from the historical period (in blue) to the future projections (in orange) toward higher minimum temperatures on wet days (top row). In the Sierra Nevada and Lake Tahoe Basin, this will mean a continuation of the trend already identified in the historical record of a greater proportion of precipitation being delivered as rain rather than snow.

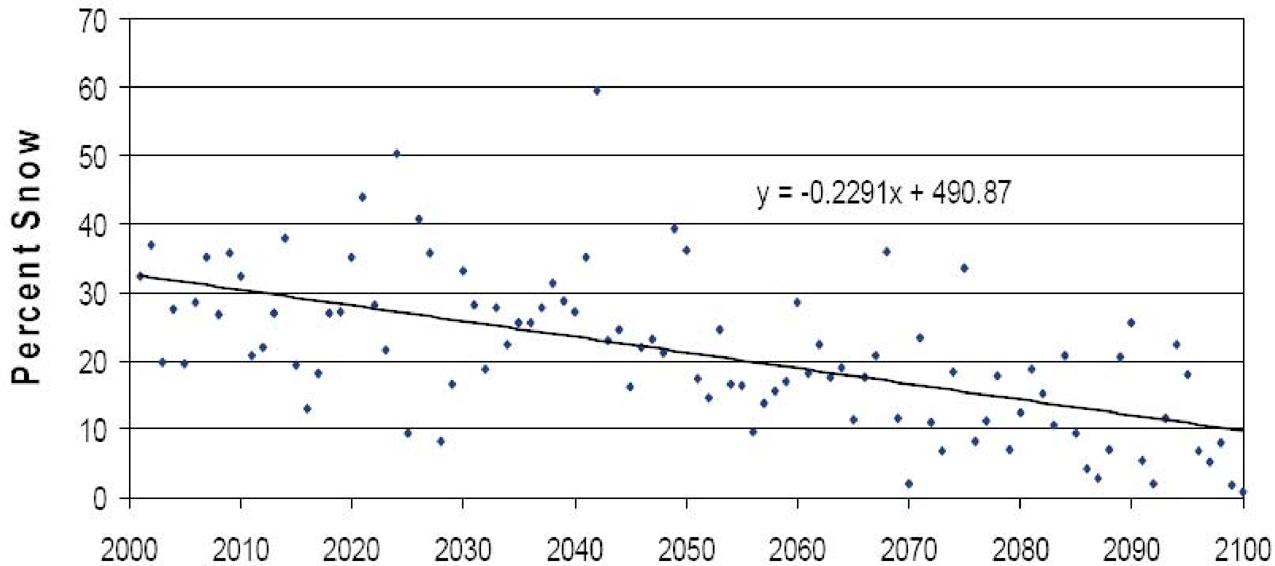
In addition to regional studies, several recent modeling experiments specific to the Lake Tahoe Basin indicate reductions of the proportion of precipitation delivered as snow. Simulations by Coats (2010b) suggest a 17-22% reduction in the fraction of precipitation delivered as snow by the year 2100 (Figure 4.9; Coats 2010b). Similarly, estimates from Coats et al. (2010) indicate a somewhat wider range of approximately 9-25% reduction in precipitation as snow for elevations near the Lake level (6230 ft) (Figure 4.10).

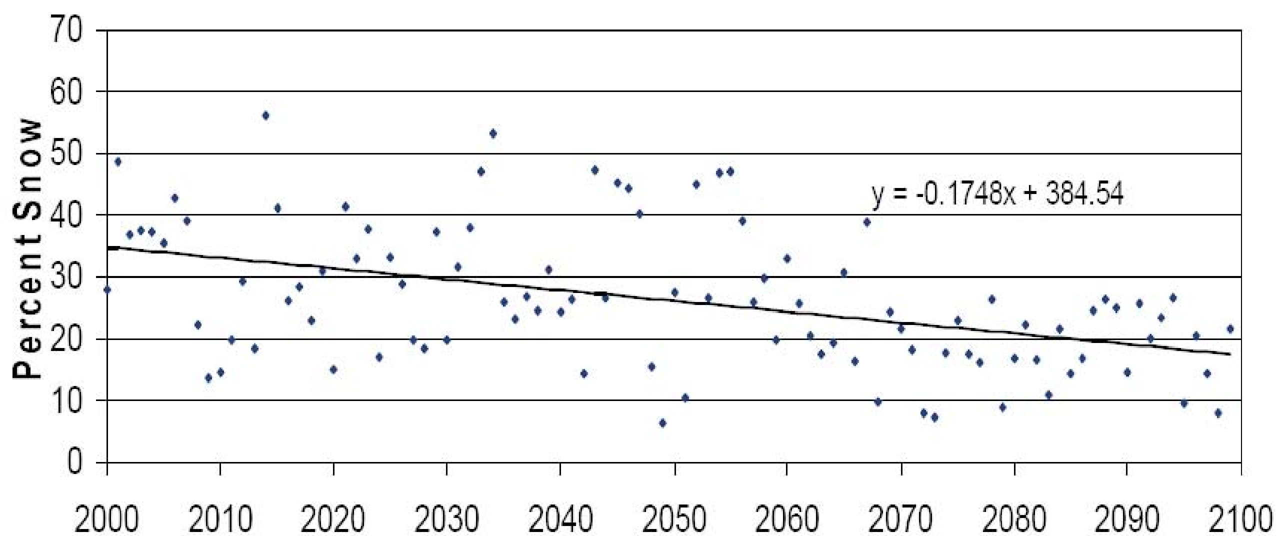


Percent differences in 30-year mean annual total precipitation for Sacramento area of early (2005–2034), middle (2035–2064), and late (2070–2099) twenty-first century projections relative to 1961–1990 historical means for each of six GCMs for both SRES B1 (lower; blue) and SRES A2 (upper; red) emissions scenarios. Source: Cayan et al., 2009

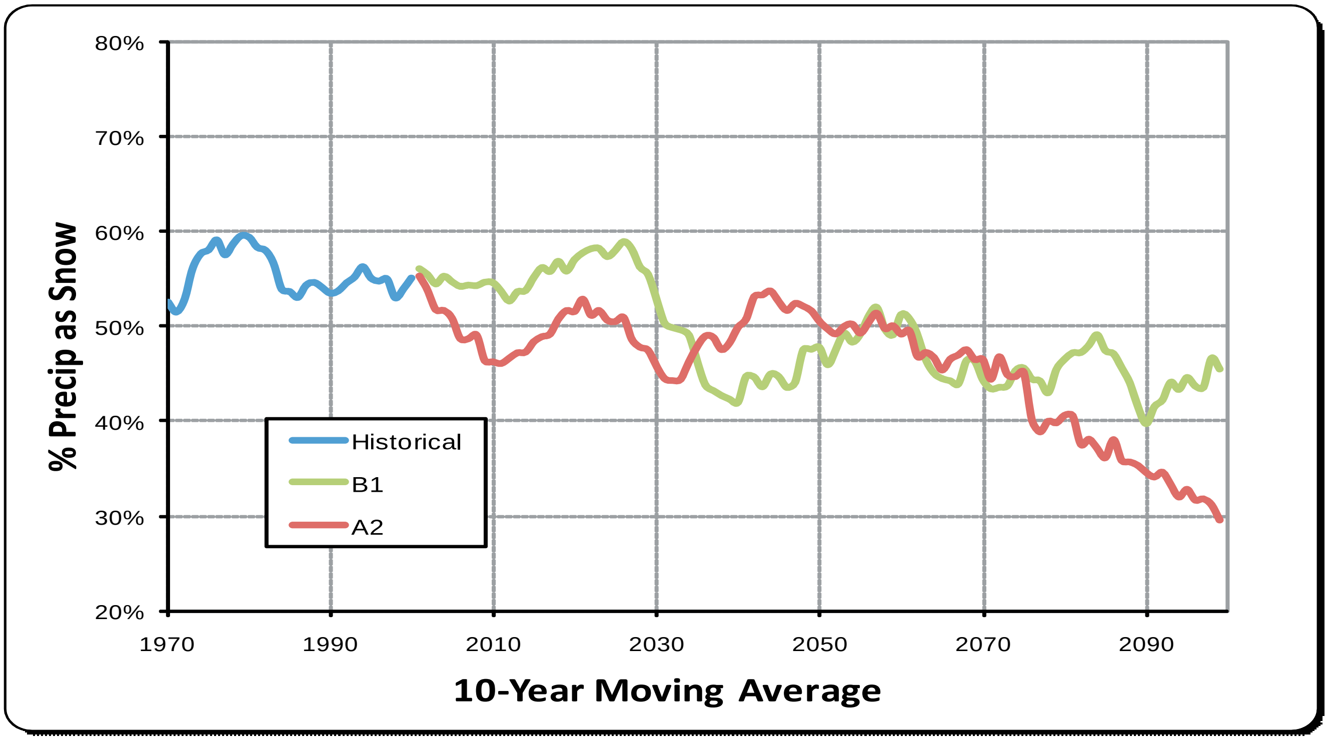


Distribution, binned by 1°C intervals and displayed as percentages of total counts in the range from –10 to +10°C, of daily northern California minimum temperatures for November-March 1961–1990 (blue) and 2070–2099 (orange) on days that are dry (bottom row) and on days with precipitation (wet; top row). Data displays model outputs from GFDL model using the A2 scenario (left) and the PCM model using the B1 scenario (right) simulations. There is a notable shift in the frequency distribution from the historical period to the future projections toward higher temperatures on wet days (top row) making precipitation delivery as snow less likely in the future compared to the historical period. Source: Cayan et al., 2008





Average percent annual precipitation as snow projections for the Lake Tahoe Basin from the PCM climate model under the A1 (top) and B1 (bottom) scenarios. Source Coats et al., 2010



Future characteristics of the Lake Tahoe annual precipitation fraction as snow as predicted using the B1 and A2 emission scenario climatic projections input into the Lake Tahoe-customized PLRM urban hydrology model. The data indicate a reduced percentage of precipitation falling as snow at the elevation of Lake Tahoe (6200 ft) over the next century. Source: Coats et al., 2010

CHAPTER 5 - HYDROLOGIC RESPONSE PROJECTIONS

Hydrologic models use downscaled precipitation and temperature projections as inputs to predict the watershed hydrologic responses, such as snow accumulation and streamflow, to atmospheric forcing (e.g., Wilby and Dettinger, 2000). Modeling experiments have been used for more than a decade to understand how changing climate will affect watershed hydrology and how competing influences may either increase or diminish future floods in the Sierra Nevada (e.g., Wilby and Dettinger, 2000; Kim, 2005; Anderson et al., 2002). Hydrologic models are designed to capture the particular physiographic characteristics of a watershed that will influence watershed responses to climate drivers. Similar to global climate models, hydrologic models are based on quantitative algorithms that estimate responses to a series of drivers, and errors are inherent. Important sources of uncertainty in projections from hydrologic models include the choice of model structure; the emissions scenario and the climate model projections used as input data; and the details of watershed characteristic representation (e.g., Dettinger et al, 2009). A number of hydrologic or physical based models have been developed for Lake Tahoe including Lake Tahoe Watershed Model or LSPC (LRWQCB and NDEP, 2010), Pollutant Load Reduction Model (PLRM; nhc et al., 2009), site-specific HEC-RAS models, site-specific SWMM models, and Lake Tahoe Water Clarity Model (http://www.tiims.org/Science-Research/Environmental-Modeling/Lake-Clarity-Model.aspx).

Table 5.1 provides a summary of the expected Lake Tahoe hydrologic response trends over the coming century based on existing Lake Tahoe modeling efforts, statewide hydrologic studies and the general expected hydrologic responses as stated by other climate change science sources. The relative uncertainty in each potential hydrologic response is not provided because the actual hydrologic responses are strongly dependent upon the future climatic conditions, which are inherently difficult to predict with certainty (Chapter 4).

Hydrologic Variable	Spatial Context	General Change	Magnitude of Expected Change and Time Period	Primary Climatic Drivers
Snow accumulation	Sierra Nevada Region	Reduction	50-80% reduction April 1 SWE by 2070-2099[13]	Spring and summer temperature increases
Streamflow timing	Sierra Nevada Region	Earlier in year	Streamflow centroid 30-40 days earlier by 2100[86]	% of precipitation as snow; Spring/ summer temperature increase
Winter streamflow volume	Sierra Nevada Region (American River)	Increase	30-90% volume increase by 2100 (December)[53]	Winter temperature increases; % of precipitation as snow
Spring/Summer streamflow volume	Sierra Nevada (American River)	Reduction	40-50% volume reduction by 2100 (May)[55]	Increased temperatures (i.e., reduced snowpack and earlier snowmelt)
Winter soil moisture	Lake Tahoe	Increase	> 2mm increase (December-January)[21]	Winter precipitation volume increases
Summer soil moisture	Northern Sierra Nevada	Reduction	-	Increased temperatures (i.e., reduced snowpack and earlier snowmelt)
Floods	Lake Tahoe Upper Truckee River	Increased risk and magnitude	120-150% increase in 100-year flood event by 2034-2066[17]	Increased likelihood of rain on snow events; Winter precipitation event magnitude increases
Droughts	Lake Tahoe	Increased risk and severity	-1 to -7 change in Palmer Drought Severity Index[16]	Increased temperatures (i.e., reduced snowpack and earlier snowmelt)

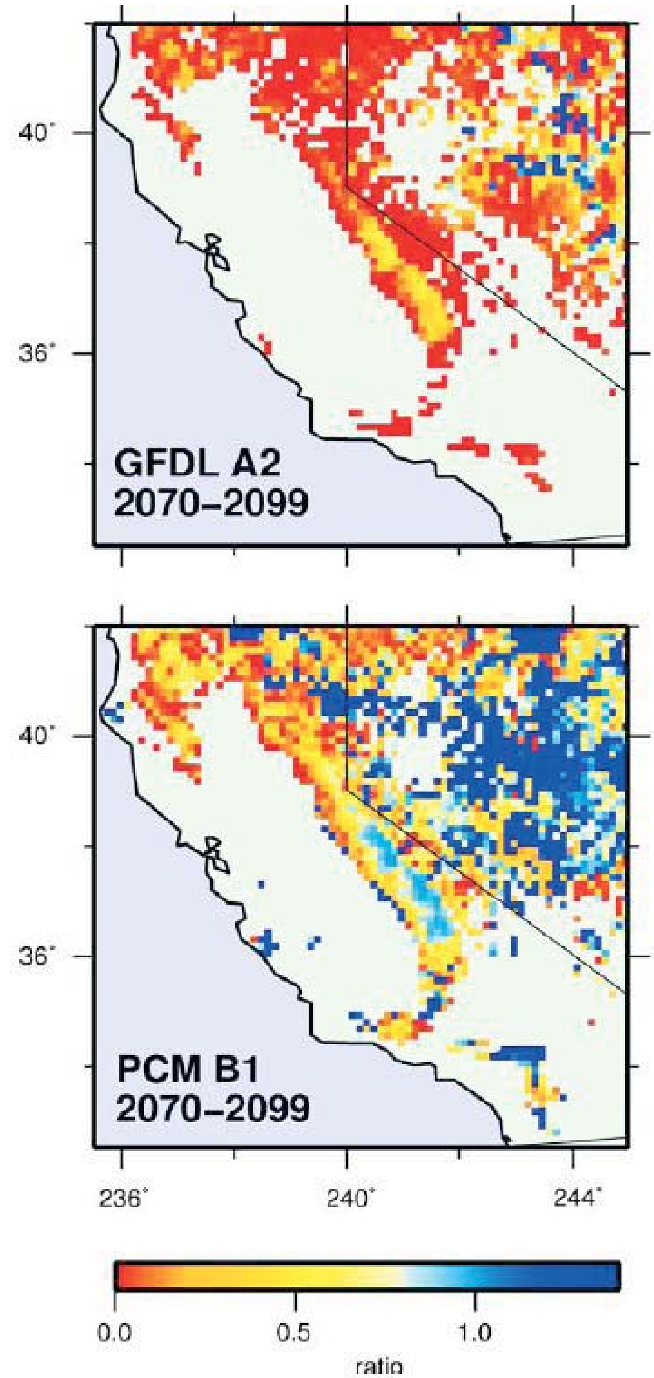
Table 5.1. Summary of potential hydrologic responses to climate change in the Lake Tahoe Basin. Note: footnotes refer to literature cited in Chapter 8 – References, listed in alphabetical and numerical order.

5.1 SNOW ACCUMULATION

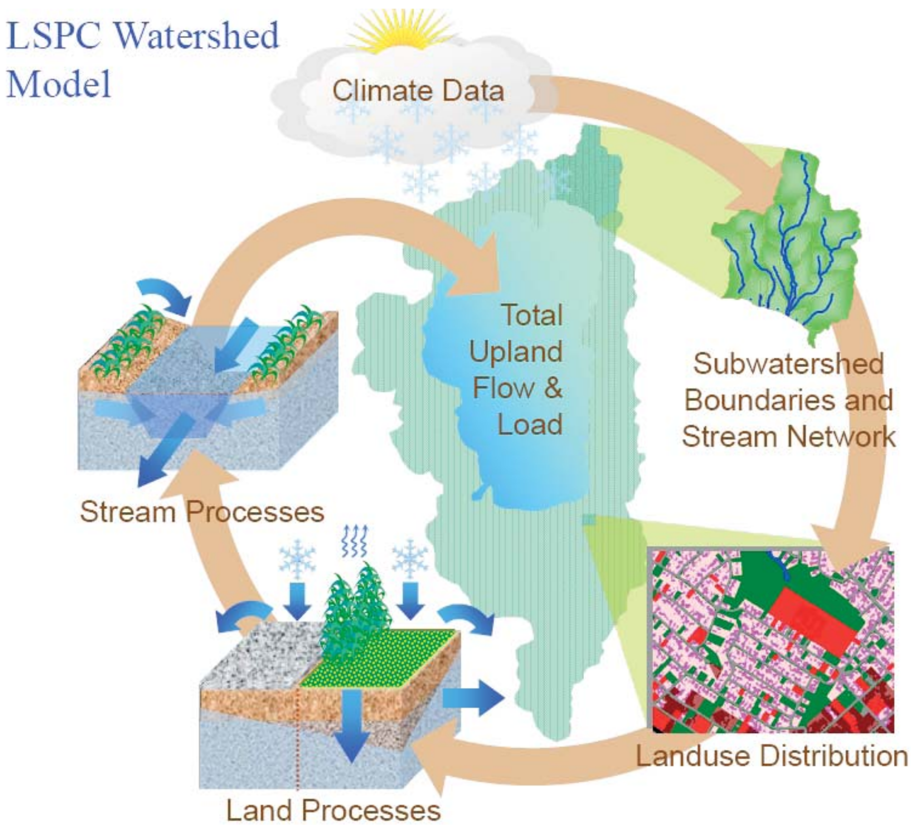
All of the models used in the Scenarios Assessments resulted in a loss of the annual snowpack volume and an increase in the elevation at which snow accumulates throughout California (Cayan et al., 2009; Cayan et al., 2008b). Earlier studies, where precipitation decreases were projected to be slight or undetectable, also produced hydrologic model simulations that yield substantial losses of spring snow accumulation across the Sierra Nevada (e.g., Hayhoe et al., 2004). Results from the Scenarios Assessment, which used the Variable Infiltration Capacity (VIC) hydrologic model, show that the Tahoe Basin is projected to have less than half of the April 1 snow water equivalent (SWE) in the period 2070-2099 relative to the historical average (1961-1990) (Figure 5.1) (Cayan et al., 2008). The GDFL model under A2 and the PCM model under B1 bracket the range of results from Cayan et al. (2008). Furthermore, both the A2 and B1 scenarios indicate reductions in April 1 SWE by 2070-2099 for the area surrounding the Tahoe Basin, with some areas showing reductions greater than 80% in SWE from 1961-1990 values. These results correspond to those by Miller et al. (2003) who found that in snowmelt dominated watersheds in California, snow accumulation on an average annual basis is expected to decrease by 50% towards the end of the 21st century.

Simulations indicate that April 1 snow water equivalent (SWE) in the San Joaquin, Sacramento and Trinity drainages, as percentages of historical (1961–1990) averages, range from +6 to −29% for the 2005–2034 period, from −12 to −42% for 2035–2064, and from −32 to −79% for the 2070–2099 period (Cayan et al., 2008b). The GFDL model produces snowpack losses nearly twice those expected by the PCM model. These results correspond with those from Hayhoe et al. (2004) and Maurer (2007) who (using the VIC hydrologic model but different climate model inputs) both found decreases in SWE in the Sierra Nevada under the A1 (or A1fi) and B1 scenarios, with the most pronounced snow losses at lower elevations. Studies generally show that snowpack losses are greatest in the higher emissions A2 scenario, which results in nearly no snow accumulating below 1,000 m, up to a 93% reduction in SWE between 1,000m and 2,000m, and up to a 73% reduction in SWE between 2,000m and 3,000m by 2070-2099 (Cayan et al., 2008b). Simulations indicate that throughout the 21st century, snow lines will move to higher elevations and the winter snowpack will be depleted more quickly throughout the year (e.g., Miller et al., 2003; Dettinger et al., 2009). Warmer temperatures and more precipitation falling as rain instead of snow is likely to cause snowmelt runoff to shift to earlier in the year (Hayhoe et al., 2004), continuing the trend that has already been observed since the early 1900s in the Tahoe Basin (Coats, 2010). The shift in the springtime snowmelt was cited as a primary driver of the snowpack loss that was found in the California Scenarios Assessment simulations (Cayan et al., 2009; Cayan et al., 2008b) and other studies (e.g., Maurer, 2007).

Model simulations using the Lake Tahoe customized LSPC Watershed Model and PLRM provide results consistent with the assumptions that the snowpack depth and duration will decrease in the Lake Tahoe Basin in the coming century. Figure 5.2 illustrates the structure of the LSPC Watershed Model, which is the hydrologic model used for the Lake Tahoe TMDL pollutant loading estimates (LRWQCB and NDEP, 2010). LSPC and PLRM were both developed and calibrated using historic meteorological SNOWTEL data from 1967-1999. The simulations were extended to 2099 using both the B1 and A2 scenarios precipitation and temperature GCM projections downscaled for the Lake Tahoe area. Figure 5.3 summarizes the LSPC-projected decreases in the duration of the annual snowpack persistence as well as significant reductions in the snowpack depth (Riverson, 2010). LSPC outputs indicate a reduced snowpack depth and duration over the next century for both scenarios.



Change in springtime snow accumulation from the VIC hydrological model, driven by climate changes from GFDL A2 (upper) and PCM B1 (lower) climate simulations. Changes are expressed as ratio of 2070–2099 April 1 snow water equivalent (SWE) to historical (1961–1990) SWE, where the projected changes in the Lake Tahoe range from a 50% reduction in SWE under the B1 scenario, up to an 80 to 90% reduction using the A2 scenario. Source: Cayan et al., 2008



Conceptual schematic of the LSPC Watershed Model, illustrating the variables and processes represented in the model. The LSPC Watershed Model was developed to estimate the relative loading of pollutants from a varieity of soucres to Lake Tahoe and used for the Lake Tahoe TMDL. Source: Riverson et al., 2010

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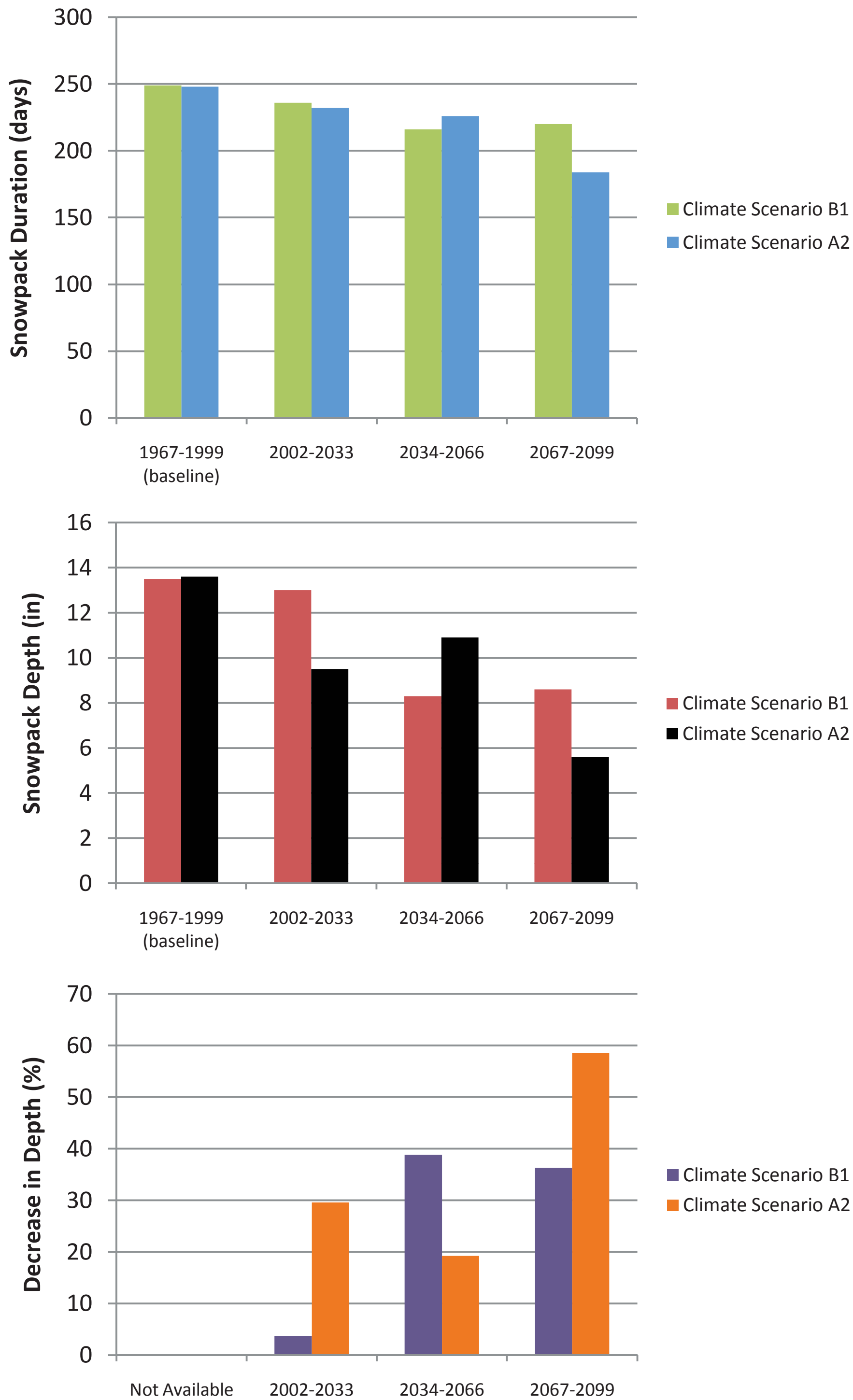
LSPC WATERSHED MODEL CONCEPTUAL SCHEMATIC

FIGURE 5.2



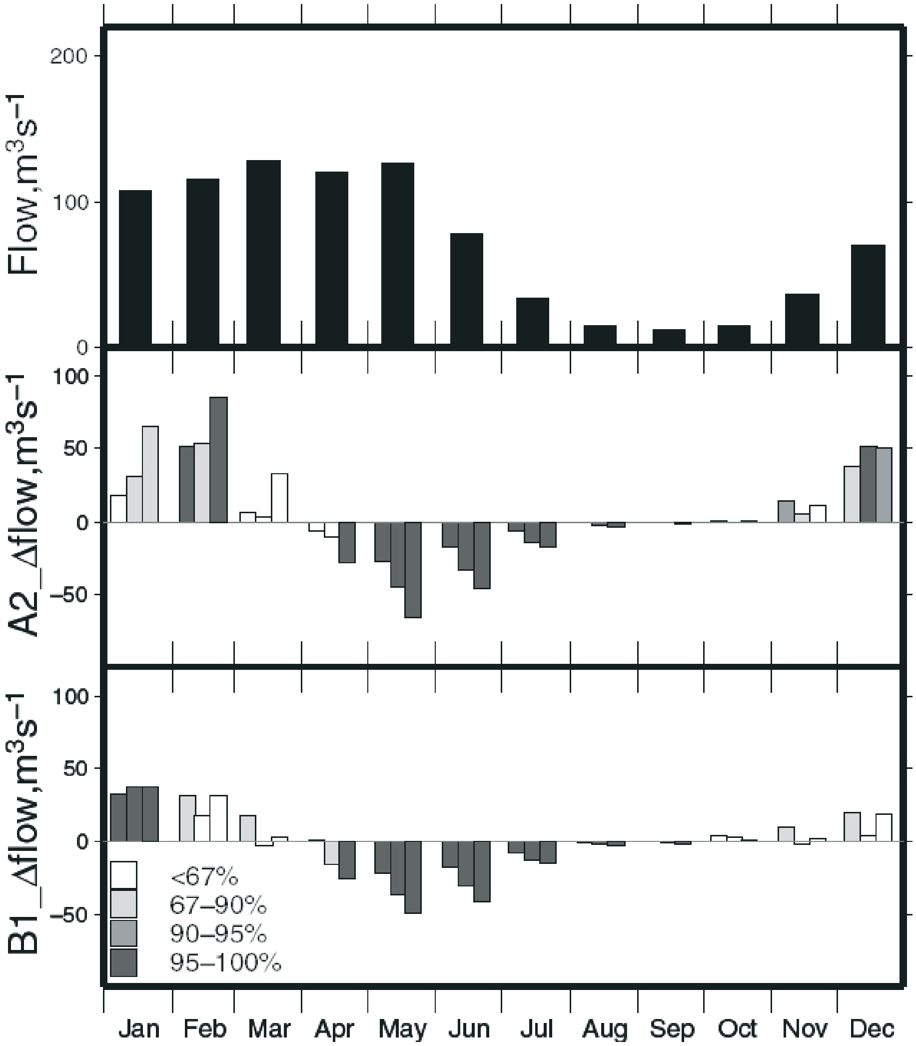
Future characteristics of the Lake Tahoe snowpack predicted using the B1 and A2 emission scenario climatic projections input into the Lake Tahoe customized LSPC Watershed Model. LSPC outputs indicate reduced snowpack depth and duration over the next century for both scenarios. Source: Riverson, 2010

5.2 STREAMFLOW VOLUME AND TIMING

Research indicates that there will be significant changes to the timing, magnitude and seasonal patterns of streamflows in the Sierra Nevada by the end of the 21st century that will affect the Lake Tahoe region. Changes in the timing of hydrograph components such as peak flows, annual flow center of mass (centroid of the annual hydrograph), magnitude of the historic spring pulse during snowmelt, and reductions in low flows (summertime baseflow) have already been observed regionally (Stewart et al., 2005) and in the Tahoe Basin (Coats, 2010). These changes are expected to continue into the future as even relatively modest climate change projections may be sufficient to create substantial disturbances in the hydrology and ecosystems of Sierra Nevadan watersheds (Dettinger et al., 2004). Projections from climate model simulations indicate that inter-annual precipitation variability in California will continue into the next century (Cayan et al., 2008), leaving high-elevation watersheds especially vulnerable to drought. Spring snowmelt is the most important contribution to many rivers that drain to the Tahoe basin and an earlier snowmelt is expected to reduce the minimum baseflow experienced in California streams (Dettinger et al., 2004).

Hydrologic simulations show that in snow-dominated watersheds a larger proportion of the streamflow volume will occur earlier in the year, but the magnitude and shift in timing is dependent on the characteristics of each basin, particularly the elevation (Miller et al., 2003). Results from Stewart et al., (2004) indicate that the annual flow center of mass (centroid of the annual hydrograph) date is projected to occur on average 30-40 days earlier in Sierra Nevada watersheds by 2100. Researchers attribute these shifts in winter and spring hydrologic patterns will result from the anticipated increased winter air temperatures rather than changes in precipitation (Stewart et al., 2004). The shift in snowmelt timing and magnitude would also cause the timing of the transition of a specific stream reach from a gaining (net shallow groundwater flux to stream) to losing stream (net stream flux to groundwater) to occur earlier in the year. This will likely reduce the summer riparian and meadow soil moisture and baseflow volumes, components of the system critical to aquatic flora and fauna.

Maurer (2007) presented a detailed hydrologic simulation study for four Sierra Nevada watersheds and found high confidence in two future hydrologic impacts: an increasing magnitude in the winter stream discharge and a decreasing magnitude in the late spring and summer baseflow. Figure 5.4 presents the projected estimates of the American River monthly discharge throughout the year during the 21st century for the A2 and B1 emissions scenarios. As expected, the A2 scenario projects much more dramatic winter discharge increases and summer baseflow reductions than the B1 scenario. Both scenarios reflect a continued winter month discharge increase and summer month baseflow decline as the century continues. Under both scenarios, the total annual precipitation is not projected to dramatically change as the declines in summer flows are offset by increases in winter flows that are driven by the projected winter precipitation increases (see Figure 5.4). However, using the American River projections as an example, the reduced storage of water in the snow pack and increased winter peak flows could influence flood control and conveyance strategies in developed areas. Similarly, the reduction in summer baseflow volumes would influence the habitat quality and quantity of aquatic species by reducing habitable reaches and reducing connectivity between those areas.



Top panel shows historical mean monthly flow for the American River basin, and the projected changes under the A2 (center panels) and B1 (lower panels) emission scenarios. Shading indicates statistical confidence. In the lower two panels, the three bars within each month indicate changes relative to the base period for early twenty-first century (2011–2040; left bar), mid–century (2041–2070; center bar) and end of century (2071–2100; right bar). Source: Maurer et al., 2007

5.3 SOIL MOISTURE

Expected climate changes are likely to create greater seasonal and inter-annual changes in soil moisture conditions in Lake Tahoe Basin watersheds. These changes are expected to result in relatively wetter soils in the winter season (Dettinger et al., 2009) and drier soils in the summer (Dettinger et al., 2004) compared to present seasonal soil moisture conditions. Figure 5.5 illustrates the predicted increase in December/January winter soil moisture for the western US. Lake Tahoe is expected to experience an increase in winter soil moisture on the order of 2 mm, which is likely in response to potential changes in timing and magnitude of winter peak runoff events and snowmelt (Dettinger et al., 2009).

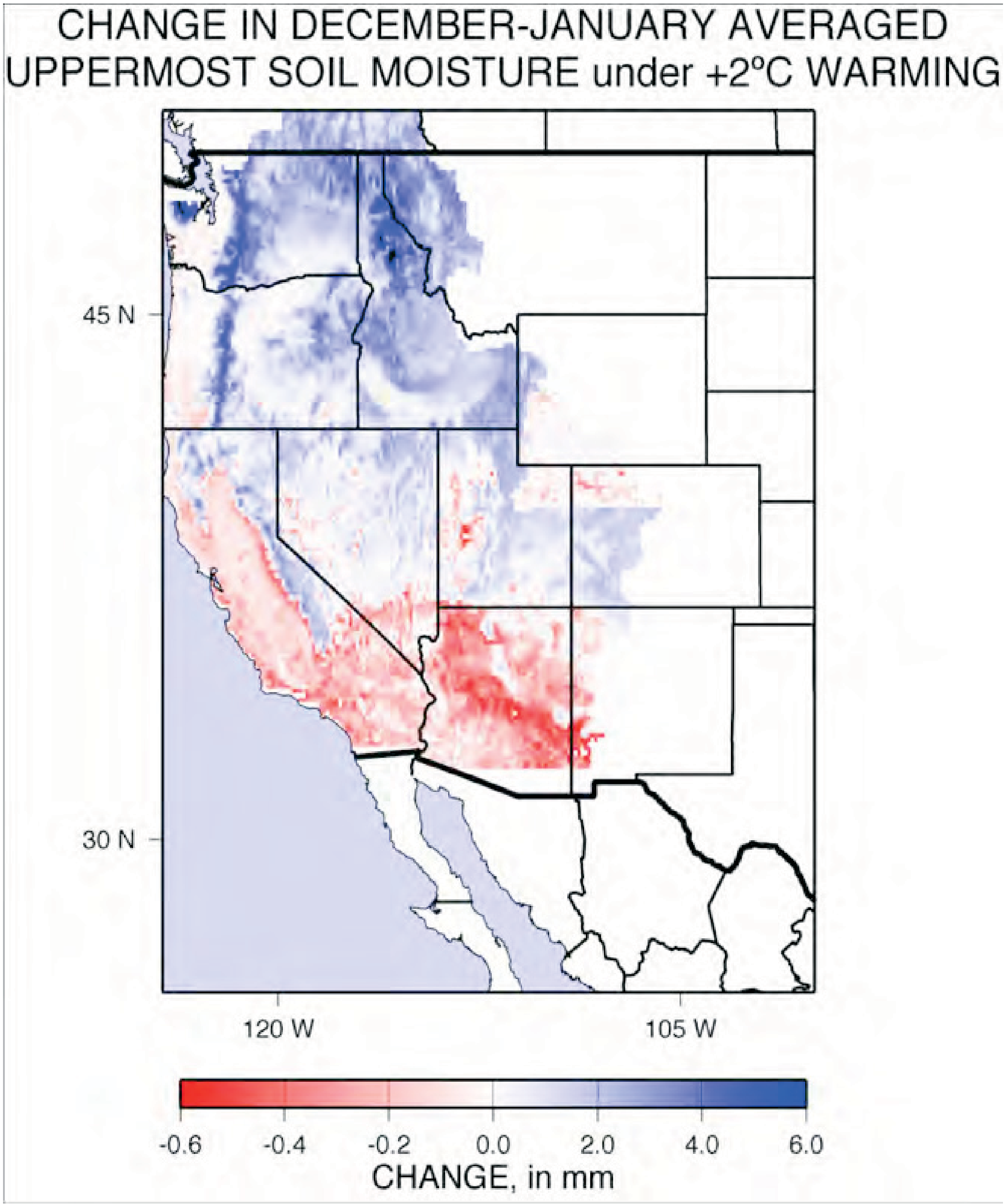
Greater potential evaporation and evapotranspiration from soils during summer months (Hayhoe et al., 2004) will create a drier watershed and riparian areas. Although there is greater potential for evapotranspiration (ET) via warmer temperatures, actual summer ET is expected to decline along with the summertime streamflows due to less moisture available for ET (Hayhoe et al., 2004). Simulations from the VIC hydrologic model indicate that warming will accentuate the summer dryness by reducing soil moisture (Cayan et al., 2009). Figure 5.6 illustrates that years with June soil moisture below the 10th percentile (red lines) become more frequent throughout the 21st century.

Soil moisture changes may result in Lake Tahoe streams converting from gaining streams (net shallow groundwater flux to stream) to losing streams (net stream flux to groundwater) earlier in the spring. The increased risk in drier summers could reduce the summer baseflow discharge in surface water streams. The surface water/groundwater interactions are critical to adjacent riparian and meadow soil moisture and summer minimum flow conditions.

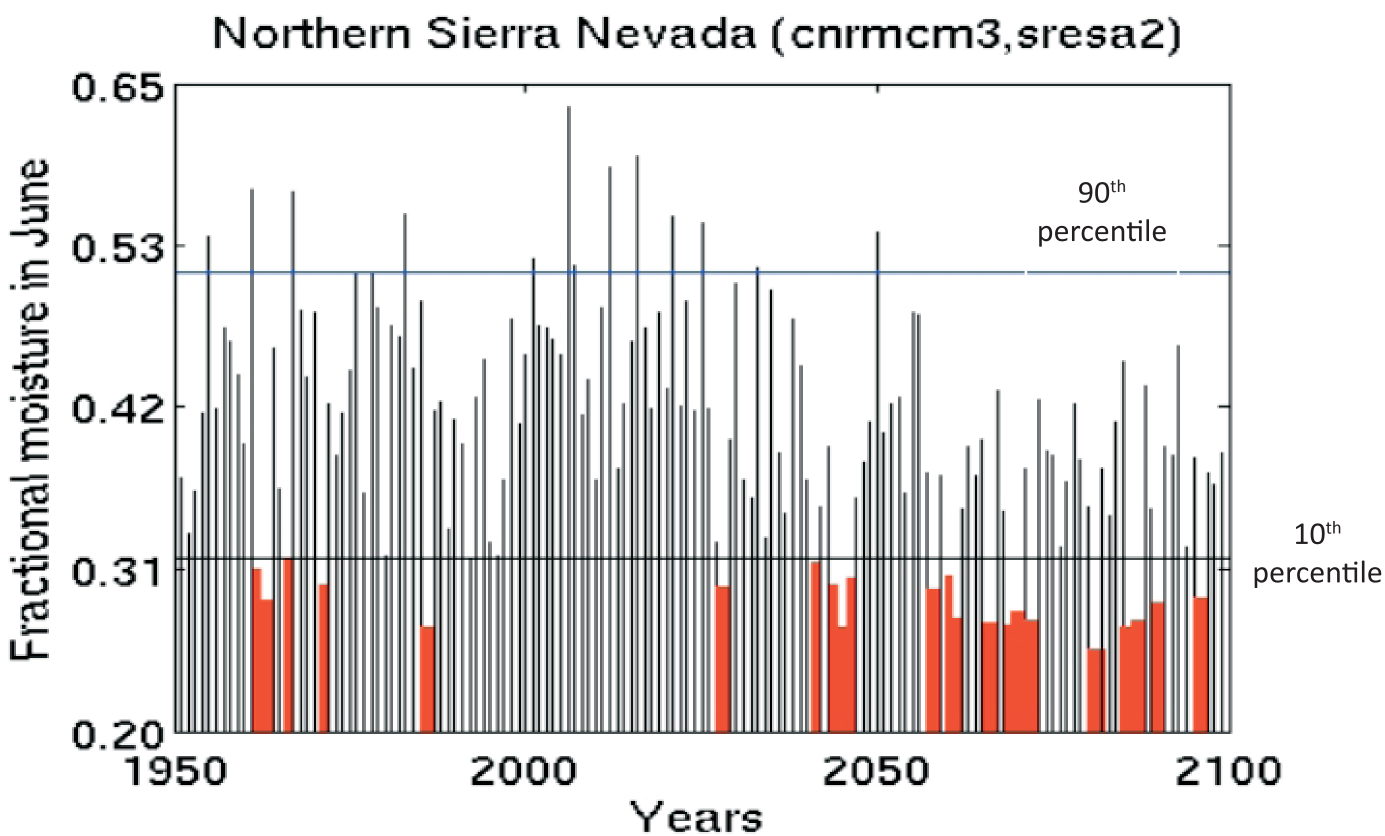
5.4 FLOODING

Although substantial uncertainty exists, several lines of evidence from hydrologic modeling experiments indicate the potential for increased frequency and magnitude of flooding. Greater frequency of extreme precipitation events in the future (Cayan et al., 2008b) and associated hydrologic responses are likely to shift flood regimes (timing and magnitude of flood events) throughout California (CNRA, 2009). Land use management decisions that have disconnected streams from their historical floodplains have reduced the adaptive capacity of riparian systems, which may become more important given projected climate changes in the future (CNRA, 2009). Lake Tahoe watersheds are likely to mirror the general tendency projected throughout the Sierra Nevada with increases in the magnitude of three-day flood events Dettinger et al. (2009) due to more precipitation at higher altitudes, wetter winter soils, earlier springtime melting of the snowpack, and higher snow lines (Hayhoe et al., 2004; Dettinger et al., 2009).

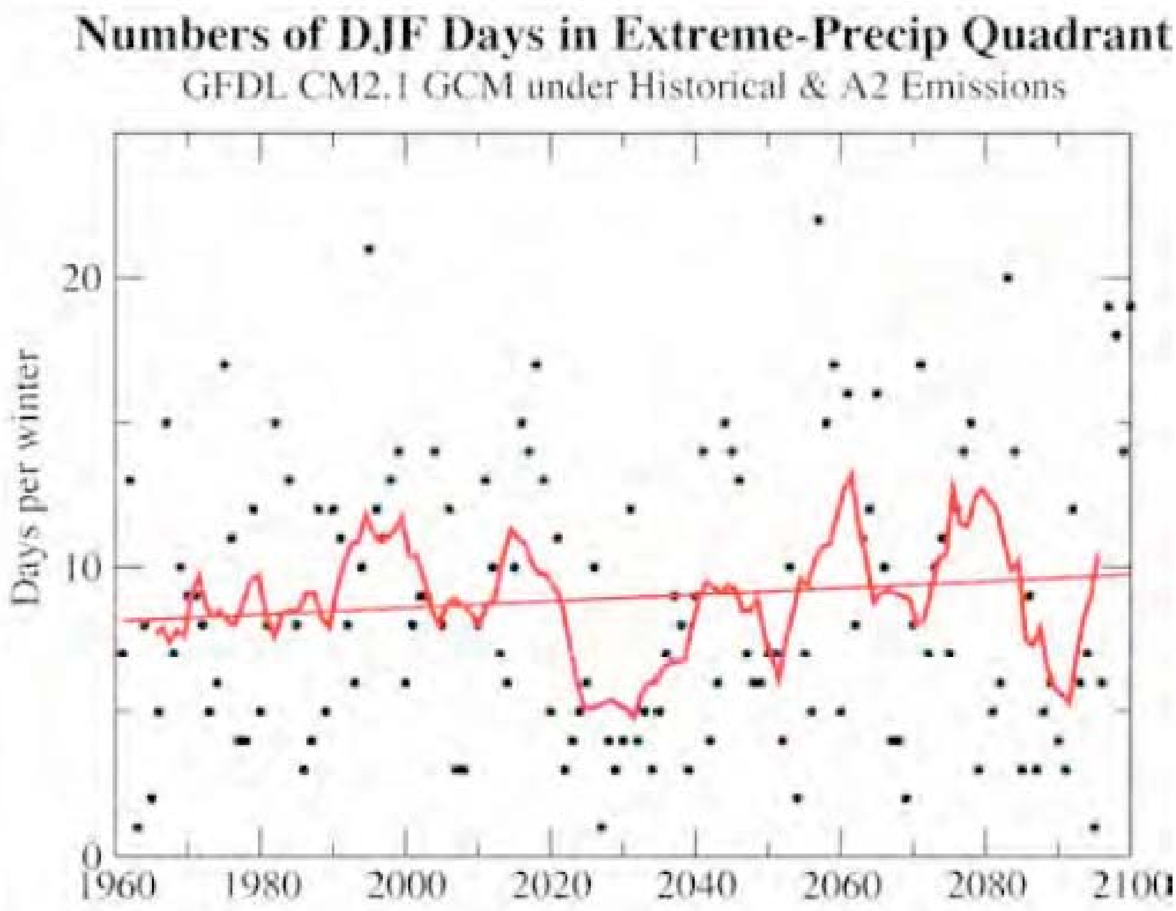
Historically, the strongest storms, which produce the most intense rains over large areas and cause the biggest floods, happen in the winter and are called “pineapple express’’ storms. These storms draw warm moist air from the tropics near Hawaii northeastward into California (Dettinger, 2004; Knowles et al., 2006). The largest recent peak discharge event in the Lake Tahoe Basin occurred in January 1997 when a “pineapple express” storm created a large rain on snow event and produced the peak discharge events of record on many Lake Tahoe streams. Dettinger et al. (2009) used climate simulations from seven global climate models and found that the frequencies of storms with “pineapple express” characteristics arriving in California increased in most of the models relative to their historical counts. Figure 5.7 illustrates the increasing trend in the number of these storms throughout the 21st century in California. Projections also indicate these storms will be relatively warmer in the coming century.



Simulated differences in soil-moisture contents in the upper 5 cm of the soil column between a simulation of hydrologic variability driven by historical meteorology, Decembers and Januaries 1950– 1999, and a similar simulation but with temperatures uniformly elevated by +2ºC (+3.6ºF); simulations were made with the Variable Infiltration Capacity (VIC) land-surface hydrology model on a 12-km grid. Note that the increases in winter soil moisture in the Lake Tahoe area are expected to increase over 2 mm. Source Dettinger et al., 2009)



Northern Sierra Nevada June soil moisture from the Variable Infiltration Capacity (VIC) hydrological model driven by the CNRM A2 simulation. Years when soil moisture is predicted to be lower than the historical 10th percentile level are shown in red. The 90th percentile and 10th percentile June soil moisture levels are indicated by blue and black horizontal lines, respectively. The frequency of very low June soil moisture is expected to increase signficiantly over the next century (Source: Cayan et al., 2009)



Projections of the number of days per winter with high potential for large precipitation events ("pineapple express" storms) using the GFDL model under historical (1960-2000) emissions and the A2 scenario (2000-2100). The straight line indicates the general increasing trend of the projected frequency of large rain events. Source: Dettinger et al., 2009

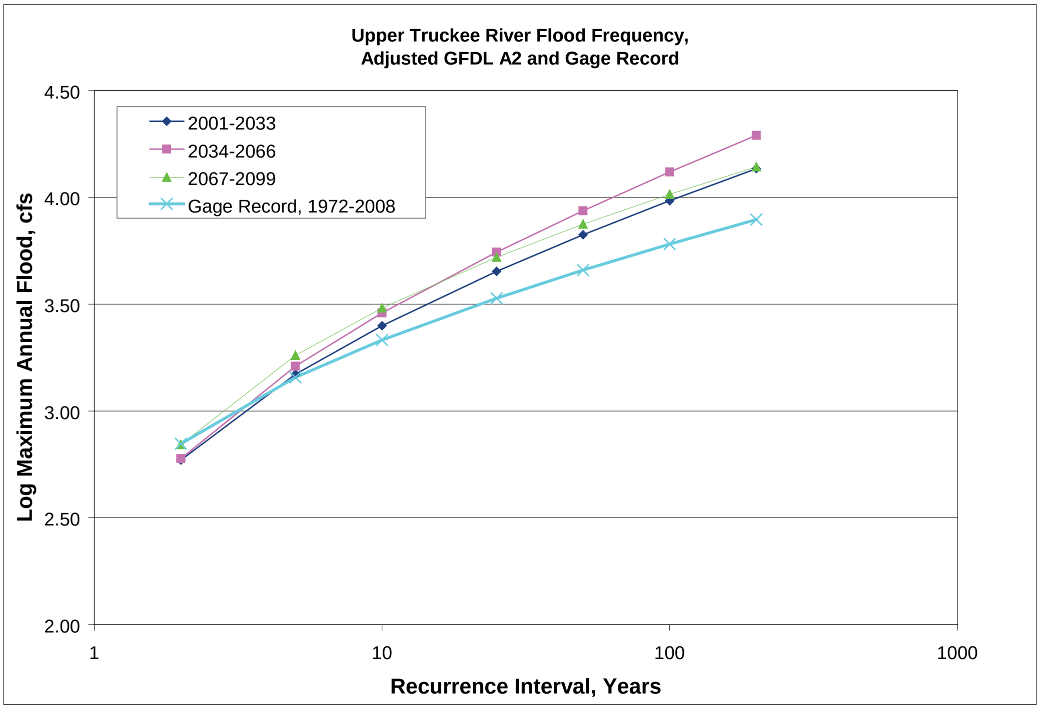
Earlier snowmelt resulting from warmer spring temperatures will cause maximum water storage in Lake Tahoe watersheds (in snow and soil pore spaces) to occur earlier in the spring. When soils are already saturated, subsequent runoff events can result in a greater fraction of surface water runoff due to the reduction in the soil infiltration capacity. Storms are expected to become approximately 3°C warmer causing snowlines to move about 500m higher during the 21st century. Higher snowlines may increase the frequency of rain-on-snow events (Dettinger et al., 2009), which may contribute to greater flood frequency and magnitude.

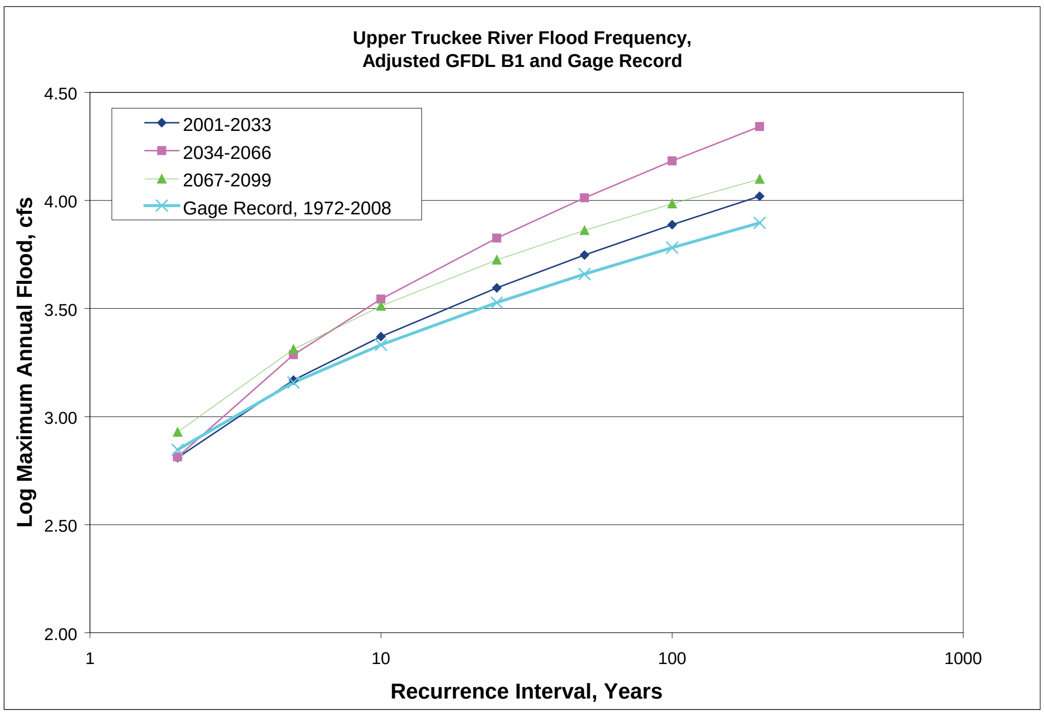
Coats (2010b) found that flood frequency in the Upper Truckee River will increase throughout the next century relative to the historical record in both the A2 and the B1 scenarios using the GFDL climate model and the LSPC hydrology model (Figure 5.8). For both sets of simulations, the changes to the flood magnitudes are the most pronounced between 2034-2066, when the 100-year flood magnitude increased by 152% in the B1 scenario and 117% in the A1 scenario (Figure 5.9). By the year 2100, the B1 scenario showed just over 60% change in flood magnitude and the A2 scenario indicated a 71% change.

5.5 DROUGHTS

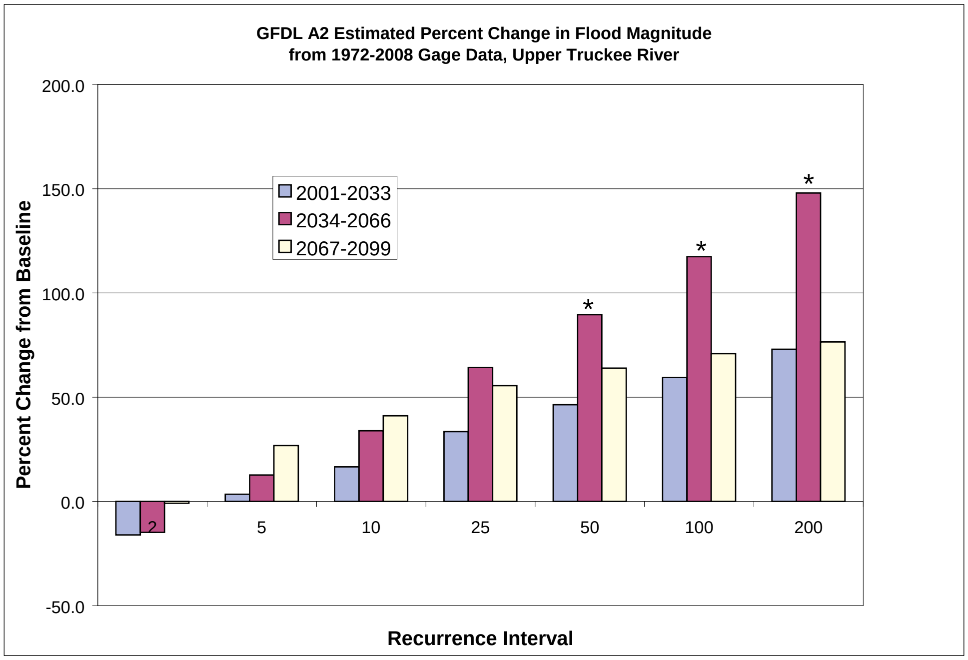
The IPCC reports that droughts are likely to become more frequent and persistent throughout the globe in the 21st century due to changes in atmospheric temperatures and dynamics (IPCC, 2007) and the anticipated hydrologic response within the Lake Tahoe region is similar. Increasing air temperatures and earlier melting of the Sierra Nevada snowpack will result in earlier spring conditions and earlier increases in evapotranspiration rates. The projected shift in snowmelt timing (Stewart et al., 2004) will significantly reduce the annual water storage that the snowpack historically has provided. In the future, years with relatively low winter snowpack followed by warmer spring and summer temperatures are expected to result in more severe drought conditions throughout California, and global climate model outputs suggest a greater frequency of these seasonal events may be likely under a range of emission scenarios.

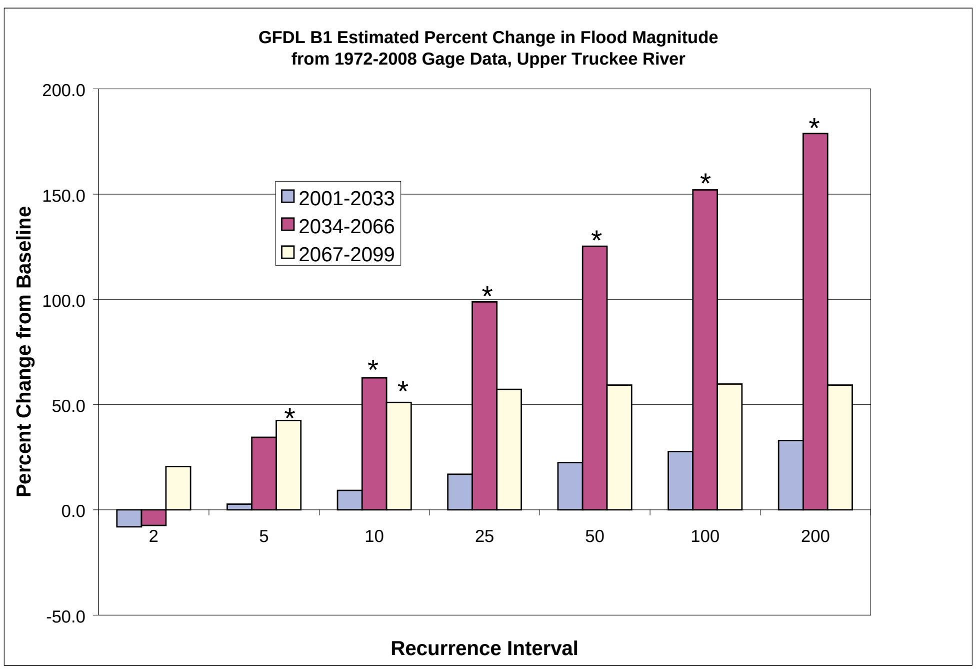
In the Lake Tahoe basin, recent calculations using climate model simulation outputs indicate that droughts will become more severe during the next century, especially on the drier east side of the basin. Figure 5.10 shows how drought severity may change under the A2 climate scenario for Tahoe City using GDFL climate model outputs to calculate the Palmer Drought Severity Index (PDSI) (Coats, et al., 2010). The Palmer Index uses temperature and rainfall information to determine relative soil moisture deficit. It is used by NOAA as the semi-official drought index to identify droughts that last several months (http://www.drought.noaa.gov/palmer.html). Normal PDSI values equal 0; the relative drought conditions are expressed as negative values and the more negative the value, the greater the projected dryness of an area. For reference, -2 is considered a moderate drought, - 3 is severe drought, and - 4 is considered extreme drought. Figure 5.10 shows a downward trend (increasing drought) to about 2045, followed by a 15-yr trend toward wetter conditions, and then a steep trend toward drought for the remainder of the century (Coats et al., 2010). In calculating the PDSI for the Tahoe basin, precipitation input is taken to be the weekly sum of rainfall plus snowmelt, so the increasing drought conditions reflect the reduction in the snowpack as a source of soil moisture in late spring and early summer.



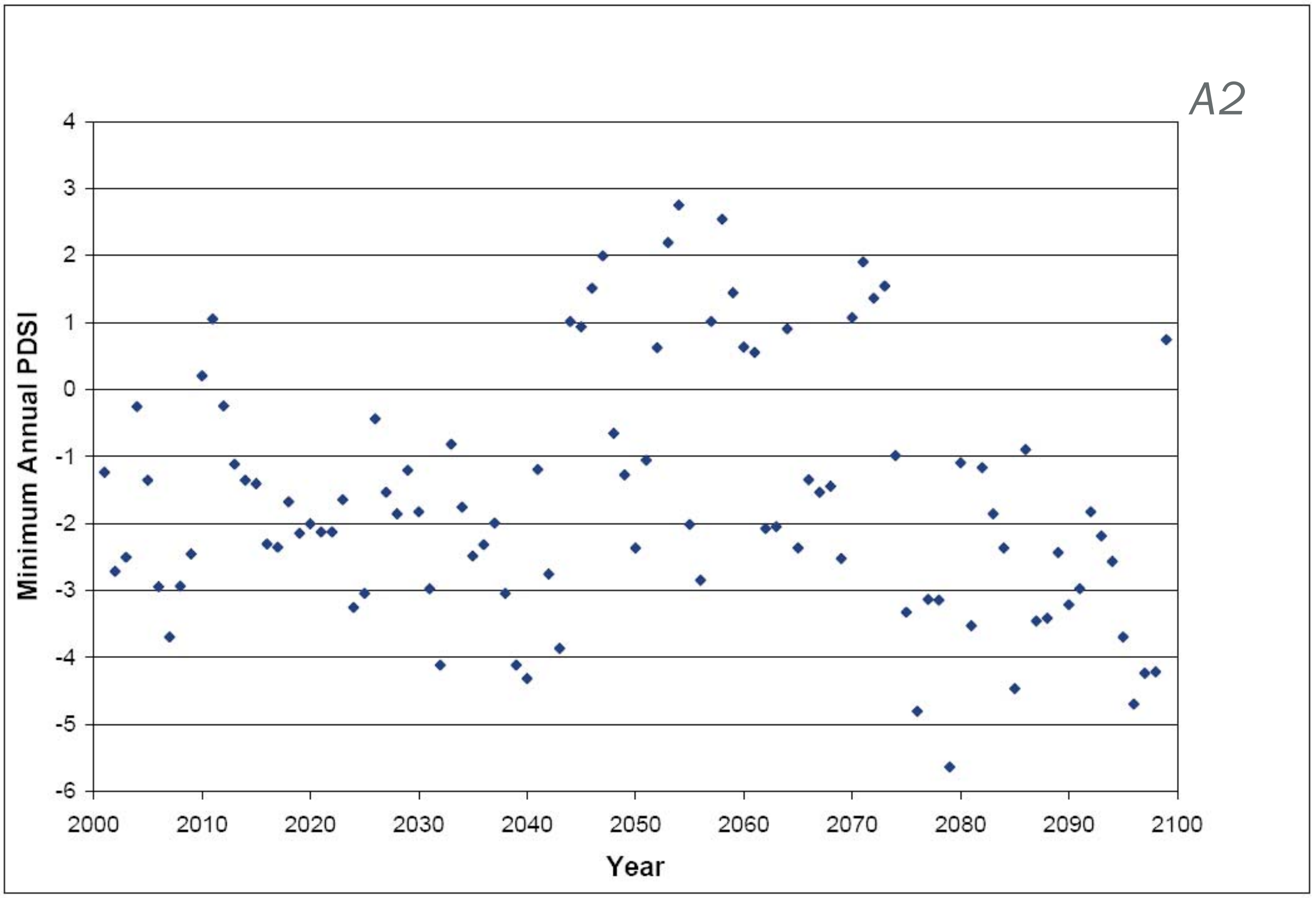


Recurrence interval for different flood stages in the Upper Truckee River for historical gage records and future projections through 2099 from the GFDL model under the A2 (top) and B1 (bottom) emissions scenarios. Source: Coats et al., 2010





Estimated percent change in flood magnitude for various recurrence intervals in the Upper Truckee River from 1972-2008 gage data under the A2 (top) and B1 (bottom) emissions scenarios. Asterisks indicate estimates that differ at the 90% confidence level from the flood frequency estimates for the gage record from the Upper Truckee River. Source Coats et al., 2010



Palmer drought severity index calculated for the Tahoe City from GFDL climate model outputs under the A2 emission scenario (Coats, et al., 2010).

CHAPTER 6 – PROJECTED CLIMATE CHANGE IMPACTS TO LAKE TAHOE BASIN SYSTEMS

In recent years, the scientific community has reached a consensus that human-induced climate change has a dramatic impact on the earth's natural and human systems (Rustad 2008, IPCC 2007). Many related physical and ecological responses show clear evidence of human influence via greenhouse gas emissions (GHG) at local to global scales (Moser et al., 2009). In the future, global climate change will increasingly interact with and intensify the pressures of a growing population on the natural ecosystems throughout California.

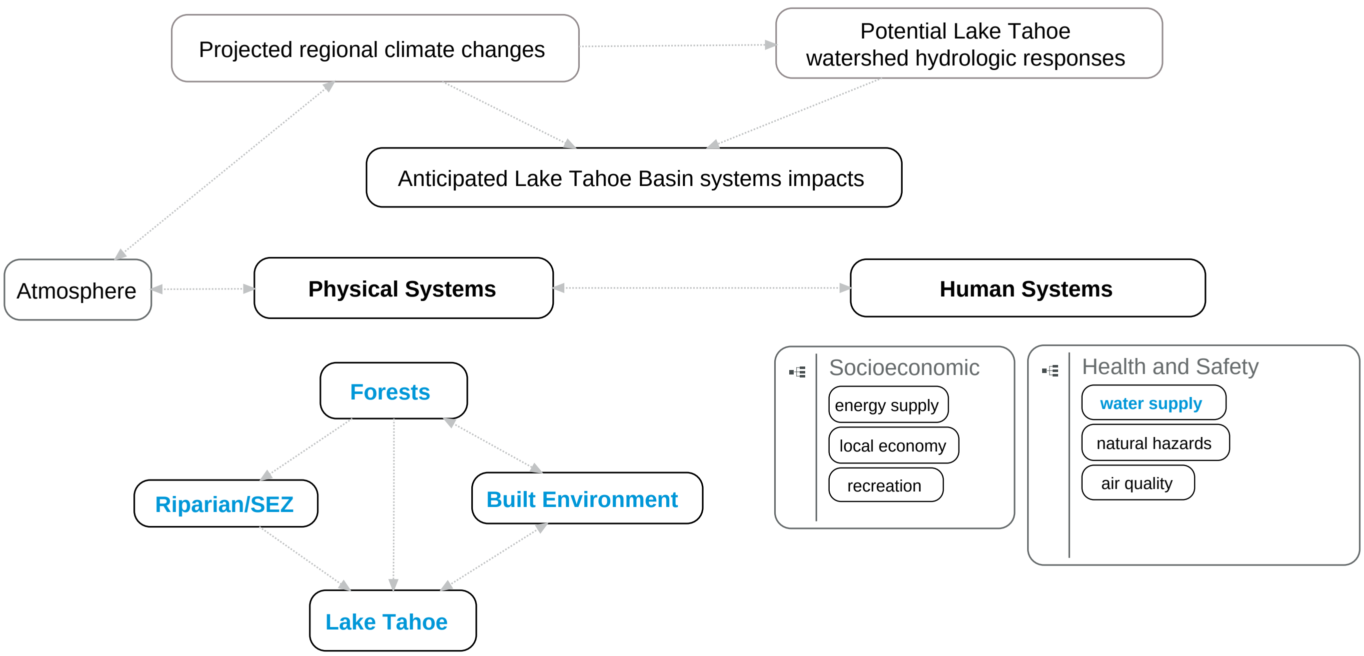
Projections of climate change impacts on physical and human systems often involve using the outputs from one type of model to drive another type of model or set of sub-models. The cumulative uncertainties associated with the use of layers of models make it difficult to rigorously test hypotheses about changes to a natural system related to climate change. Detecting a real change in highly variable systems often requires long data records, usually extending many years or decades, and the increased length of record improves our ability to detect a change beyond natural variability. However, our current understanding of how natural and human systems function and interact can allow reasonable general projections of possible shifts in system conditions relative to current and historic states.

6.1 LAKE TAHOE SYSTEMS

A Lake Tahoe system is defined as either a physical or human network that provides important services to the community. Grouping via systems provides an organizational structure to isolate specific impacts of global climate change on components of the physical and human networks within a community that is in some way functionally unique. The more the system groupings can align with planning and management efforts the more useful the system groupings will be for identifying effective adaptation strategies. Figure 6.1 presents a schematic of the systems defined for the Lake Tahoe Basin. This science synthesis focuses upon the systems relevant to aquatic resources, but this structure can be expanded to include other networks that are anticipated to be affected by global climate change.

Physical systems are groupings of actual physical resource locations within the Lake Tahoe Basin that are clearly identifiable and can be delineated, i.e., atmosphere, forests, riparian and stream environment zone (SEZ), built environments, and Lake Tahoe. A SEZ consists of a stream and its drainage as well as marshes and meadows. Built environments include any feature on the landscape that has direct human value including structures, real estate, roads, bridges, etc. Human systems include a network of programs, resources or issues that may be potentially affected by climate change. There is an inherent movement of energy and mass within and between each of the physical systems; thus the interactions between systems will indirectly affect other systems within the Basin. Climate change may alter the timing, magnitude, and spatial patterns of these interactions within and between systems in the Lake Tahoe Basin. In many instances, human systems rely upon and can be strongly influenced by the physical system function (e.g., water supply, forest fires, recreation, etc.).

Changes to the state, function, or structure of natural and human systems in the Tahoe Basin resulting from warming temperatures have already been detected and are expected to continue. The functional relationship between these projected future climate changes, hydrologic responses and Lake Tahoe Basin systems impacts are summarized in Figure 6.1. Table 6.1 lists potential impacts to Lake Tahoe physical and human systems as a result of projected climate and hydrologic changes as outlined in Chapter 6, and includes only those expected impacts that have moderate to high sensitivity to climate change impacts. For example, recent Tahoe data analysis has shown



Projected regional climate changes and potential local hydrologic responses have been used to develop a number of potential anticipated impacts to Lake Tahoe physical and human systems. Arrows indicate primary directions of energy and mass movement between the physical systems; Forests, Riparian/SEZ, Built Environment, and Lake Tahoe. This science synthesis is focused upon the potential impacts to aquatic resources, and thus limited to the systems denoted in blue. Other systems are provided as place holders to illustrate the broader application of this organizational structure.

that stormwater water quality changes are more sensitive to changes in pollutant reduction strategies than climate change and its associated impacts (Wolfe, 2010).

The content of Table 6.1 has been interpreted from Tahoe-specific observations and studies (e.g., Tahoe Environmental Research Center research), regional studies in the western US and California (e.g., studies by US Forest Service, California Scenarios Project, Consortium for Integrated Climate Research in Western Mountains), and global-scale climate change science (e.g., IPCC reports). The anticipated system responses discussed in this chapter are not comprehensive, but instead focus on responses related to the health of watershed and aquatic systems in the Lake Tahoe Basin for which there is a developed body of scientific information. While forests do not possess aquatic resources per se, the forest conditions and associated ecosystem are strongly related to the other physical systems defined in Table 6.1, and thus potential impacts are included in this science synthesis. Information on potential impacts specific to the Sierra Nevada region or the Lake Tahoe Basin was used whenever possible, and concepts are often borrowed from California or western US studies.

System	Expected Impacts
PHYSICAL SYSTEMS	
Forests	• Increased risk of wildfire frequency, extent, and intensity • Shift in the distribution and range of forest flora and fauna • Increased tree mortality rates • Reduced forest biodiversity
Riparian (SEZ)	• Changes in soil moisture dynamics • Increased erosion risk • Increased stress on cold water fish species • Reduced riparian (SEZ) biodiversity
Built Environment	• Increased flooding risk
Lake Tahoe	• Reduced frequency of lake water column turnover • Increased risk of low dissolved oxygen in deep water column • Reduced lake biodiversity
HUMAN SYSTEMS	
Water supply	• Increased risk of water use conflicts

Table 6.1. Lake Tahoe Basin potential impacts of projected climate and hydrologic changes, listed by system. *Note: Only impacts evaluated to have a moderate to high sensitivity to climate change are included in Table 6.1; however a number of potential impacts relevant to Lake Tahoe aquatic resource managers are discussed in the text.*

6.2 PHYSICAL SYSTEM: FORESTS

Climate changes and associated impacts are likely to result in a number of complex changes to Tahoe forests. Since forested watersheds of the Lake Tahoe basin drain to the streams and ultimately to the lake, climate change impacts in the forests will have important impacts related (directly and indirectly) to aquatic resources (see Figure 6.1). Drivers of change include greater seasonal fluctuations in soil moisture availability and increased frequency of disturbance events. Future climate conditions have the potential to substantially alter the composition and function of forest ecosystems. Table 6.2 details the main potential impacts to the forest system.

Forest System Impact	Causal Factors	Examples
Increased wildfire frequency, extent, and intensity	Increased fuel buildup due to more rain during winter; Hotter, drier summer conditions	37-94% increase in forest fire frequency in Sierra Nevada by 2085 using A2 scenario.[9]
Shift in the distribution and range of forest flora and fauna	Increased disturbance frequency (i.e., wildfires); Increased air temperatures; Drier summer conditions	Subalpine conifers currently exist at the upper elevation ranges in the Sierras, thus many subalpine species may be replaced with species lower elevation biotic zones.[9,50]
Increased tree mortality rates	Temperature increases, moisture stress, Increased susceptibility to insect infestations	Recent increases in tree mortality rates in 87% of plots across the western U.S.[92]
Reduced forest biodiversity	Temperature rise can alter seed production, seedling establishment, growth, and resilience; Increased risk of insects and pathogen spread due to climatic changes and increased disturbances	Conditions more favorable for tolerant species, increased physical stress (e.g, temperature and soil moisture), and increased competition from tolerant species.[9]

Table 6.2. Potential climate change impacts on the forest system in the Lake Tahoe Basin, including causal factors and examples.

INCREASED RISK OF WILDFIRE FREQUENCY, EXTENT, INTENSITY, AND SEVERITY

The California Draft Climate Adaptation Strategy states, "the most significant climate change risk facing California is associated with the increase in wildfire activity (CNRA, 2009)". Warmer spring and summer weather, reduced snowpack, earlier snowmelt, and longer drier fire seasons can be expected to increase fuel hazards and ignition risks (Westerling, 2006). Given that these climate changes are projected to continue there will be a continued risk of large damaging forest wildfires in the future (Running, 2006). Wildfire regime characteristics likely to be affected include the amount of area burned (extent), how often they occur (frequency), the time averaged amount of energy released during a fire (intensity). Climate conditions that increase wildfire intensity and duration will result in increases in wildfire *severity* (Running, 2006), which is a measure of the biomass alteration resulting from fire (Keeley, 2009). Climate change effects on fire regimes will partially depend on resource management decisions including fuel alteration (McKenzie et al., 2004).

Historically fire occurrence in the western United States has been associated with higher spring and summer temperatures and earlier spring snowmelt, and strongly associated with inter-annual changes in weather as well as decadal climate changes (Lenihan et al., 2008). To investigate changes in wildfire regimes associated with future climate conditions, researchers use outputs from global climate models to drive landscape ecosystem models that include wildfire disturbances (e.g., Fried et al., 2004). Despite substantial uncertainties associated with understanding how ecosystems will respond to climate changes (Lenihan et al., 2008; Hurteau and North, 2008), a number of modeling experiments provide useful information about how wildfire regimes are likely to change in the future.

An extended fire season due to higher spring and summer temperatures and earlier spring snowmelt appears to be increasing the number of large wildfires and wildfire intensity throughout California and the Sierra Nevada (CNRA, 2009). Statewide, simulations show that the number of wildfires associated with the higher emissions scenario (A2) is substantial, with statewide increases ranging from 37 to 94 percent by 2085 (CNRA, 2009). Simulations completed by Lenihan et al. (2003) for the 21st century showed that total burned area increased compared to the historical period for two climate scenarios. They ascribed changes to the increase in fuel buildup during wetter winter seasons followed by dry summer conditions and note the potential for increasing fire intensity and frequency resulting from the effects of pest outbreaks. Modeling by Hurteau et al. (2009) provides evidence that increases in precipitation variability coupled with increases in nitrogen deposition from fossil fuel consumption are likely to result in increased productivity levels and significant increases in forest understory fuel loads. While it was not modeled explicitly by Hurteau et al. (2009), the increases in fuel loads may increase fire intensity in a way that moves Sierran fire patterns towards larger, more regionally synchronous fire events (Hurteau, et al., 2009). Similarly, simulations by Fried et al. (2004) showed that future climate scenarios produced higher intensity and faster spreading fires in most locations, with 41% greater area burned and 125% more fires that escaped from containment in the Sierra Nevada region.

Areas with distinct hydrologic and fire regimes throughout the west may respond differently to climate change scenarios. Westerling and Bryant (2008) found that in energy limited fire regimes, such as in Sierra Nevada forests, simulations using the GFDL model under the A1 and B2 scenarios showed an increased probability of occurrence of large fires. Conversely, they found that risk of large fires may be reduced in moisture limited environments. Westerling et al. (2006) calculated an index of forest vulnerability to more frequent wildfires as a function of the distribution of forest area and the sensitivity of the local water balance to changes in the timing of spring snowmelt (Figure 6.2). They used the percentage difference in the moisture deficit (cumulative difference between potential evapotranspiration and actual evapotranspiration) to measure drought stress in plants. The warmer colors in Figure 6.2 shown in the northern Sierra Nevada, including the Lake Tahoe Basin, indicate areas that are highly vulnerable to more frequent fires in the future.

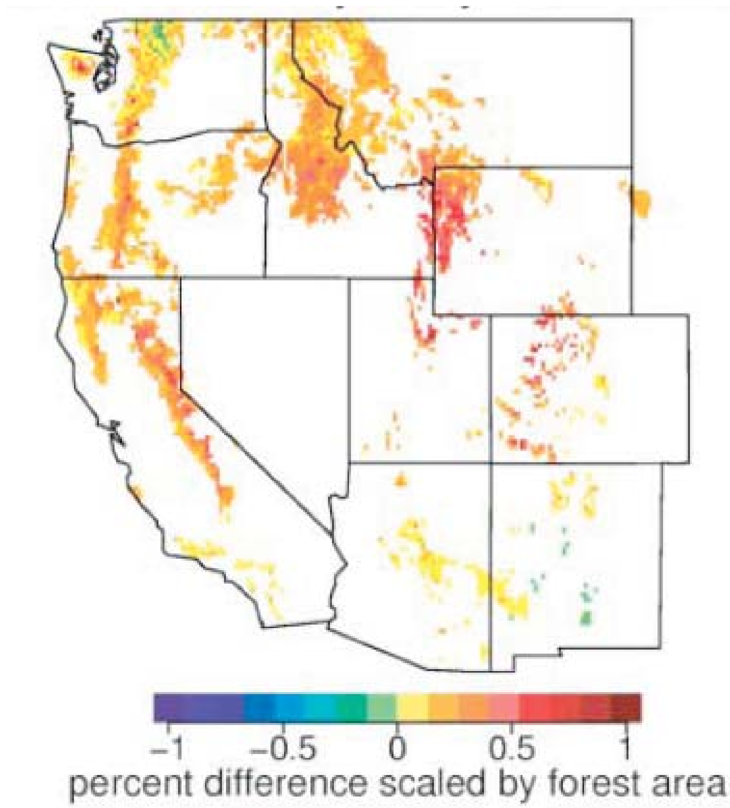
Wildfires will have indirect impacts on watershed health including stream morphology changes, water quality impacts, vegetation conversions from forests to shrublands or grasslands, habitat fragmentation, and release of CO_2 to the atmosphere from smoke (CNRA, 2009). Intense rain events on recent and severely burned areas can result in significant increases in fine sediment loading to the adjacent stream. The amount of biomass consumed by wildfire is estimated to at least double in the western United States during the 21st century under several future climate scenarios (Bachelet et al., 2001). Given the projected changes in wildfire regimes, western US forests may become a source rather than a sink of carbon dioxide to the atmosphere in the future, thereby magnifying the threat to local ecosystems (Westerling et al., 2006).

SHIFT IN THE DISTRIBUTION AND RANGE OF FLORA AND FAUNA

Moser et al., (2009) notes a number of important ecosystem changes that are likely to occur in the Sierra Nevada forests that may contribute to species assemblage changes over time:

- Phenological life cycle events, such as blooming, migration, insect emergence, leaf unfolding, coloring and fall, fruit ripening, breeding, occurring earlier in spring and/or later in fall,
- Species interactions becoming decoupled from each other as individual species react differently to warming, and
- Biomass increasing due to warmer temperatures, a longer growing season, and higher CO_2 levels.

As the rate of climate change increases some tree species may not be able to adapt to new climate patterns and hydrologic impacts. Globally, terrestrial plant and animal species are shifting poleward and to higher elevations towards cooler temperatures. Entire species populations are increasing in some areas and declining in others (CNRA, 2009). Alpine and subalpine forests and associated plant species are particularly vulnerable because they currently exist at the upper range of elevations that exist in the Sierra Nevada. Forest response to climate change



Estimated forest vulnerability to more frequent wildfires as a function of soil moisture differences resulting from the change in spring snowmelt timing. Percent difference in the soil moisture deficit (cumulative difference between potential evapotranspiration and actual evapotranspiration) is scaled by forest area to indicate areas that are highly vulnerable to more frequent fires in the futures (red shades). Source: Westerling et al., 2006 will involve complex interaction of location specific landscape factors such as physical habitat attributes, stressors, climate changes, and land-uses that may create substantial heterogeneity in the extent and rate of ecosystem shifts (Millar, et al., 2007). Ecologists are skeptical that plant communities will migrate intact, so forest and range communities may change in species composition as they migrate to elevations or latitudes where the climate conditions exist that they can tolerate (CNRA, 2009). Since individual members of species assemblages will not necessarily respond in the same way to climate changes, the composition of the flora and fauna in these communities will change as climate conditions and disturbance frequency change over time. System function can be maintained as the community composition changes over time, however, warming temperatures will reduce suitable area for alpine and subalpine forest communities in the Tahoe Basin.

Species that are unable to shift their ranges due to habitat loss or landscape fractionation risk eradication from the area. Statewide modeling simulations that represent interactions of temperature, wildfire, CO_2, and other climate effects are projecting declines in the density and distribution of conifer forests and concurrent increases in hardwood forests and grasslands (CNRA, 2009). In a study of ponderosa pine forest changes near Placerville, CA between 1934 and 1996, researchers found that the western edge of the forest moved an average of 4.4 miles (7.1 km) eastward and shifted upward by about 637 feet (193 meters), and the previously ponderosa-dominant areas were being replaced by non-conifer species (e.g., oaks; Thorne et al. 2006). Modeling experiments by Lenihan et al.(2003), indicated that warming temperatures are likely to promote the advancement of shrub dominated ecosystems into areas that are currently occupied by alpine and subalpine forests of the Sierra Nevada.

INCREASED TREE MORTALITY RATES

Individual tree species responses will vary but the synergistic effects of climate change and wildfires are expected to encourage invasive species, and may lead to a loss of forest habitat due to increased risk of tree mortality (McKenzie, et al., 2004). A recent analysis of tree mortality information collected over the last five decades in the western United States, including older established Sierra Nevada forests, determined that trees have been dying at a faster rate in recent decades (Van Mantgem, et al., 2009). The authors found positive correlation between tree mortality rates and both temperature and water deficit; and they cite regional warming and consequent drought stress being the most likely drivers of the tree mortality changes (Van Mantgem, et al., 2009).

Attacks from bark beetles reduce tree growth and hasten decline, mortality and subsequent replacement by other tree species. As trees become stressed through deficiency of moisture availability, their insect resistance mechanisms are compromised and are more susceptible to bark beetle attack (Fettig et al., 2007) which may reduce the number of beetles necessary for to kill a tree (Bentz et al., 2010). Predictions from population models suggest future climatic changes may result in movement of temperature suitability for bark beetles to higher latitudes and elevations (Bentz et al, 2010), which may influence tree mortality rates in the Tahoe Basin.

Although relationships between bark beetle outbreaks, moisture stress, and wildfire are complex and poorly understood, a number of interactions between these factors may be anticipated. For example, climate change induced shifts in bark beetle outbreak frequency and intensity may indirectly affect patterns and severity of wildfire by altering the composition of forest stands (Jenkins et al., 2008). Drought and other processes can homogenize host-tree species age and structure which may indirectly contribute to the extent of mortality events. Bentz et al. (2010) note that bark beetle outbreaks driven by climate change may push some forest ecosystems beyond the historical resilience boundaries, causing irreversible ecosystem regime shifts.

REDUCED FOREST BIODIVERSITY

Biodiversity and other ecosystem level impacts associated with climate change are very difficult to predict due to complex interactions between ecosystem components that are often difficult or impossible to model explicitly (e.g. Hurteau et al., 2009). Consequently, the following discussion about biodiversity impacts relies heavily on general ecosystem science principles rather than discrete predictions from numeric models that have been previously discussed.

Biodiversity can be defined as the number and variety of species of plant and animal life within a given region. It is a measure of the resilience of an ecosystem, and a higher level of biodiversity indicates a greater number of functional habitats and niches available for a wide range of species to occupy and survive. Many expressions of ecosystem or trophic structure function influence the degree of biodiversity, and these functional expressions can be affected by climate change. For example, increased inter-species competition for resources may result in a reduction of biodiversity due to the competitive advantage of species more tolerant to climate changes (e.g., more frequent heat waves) or climate change impacts (e.g., wildfire regime changes). Biodiversity can be used to express the condition over a range of spatial and community scales such as the complete region (Lake Tahoe Basin biodiversity); a system (riparian (SEZ) biodiversity), or biological communities (fisheries biodiversity or songbird biodiversity). For the purposes of this science synthesis, the climate change impact “reduced biodiversity” is used to simplify the communication of ecosystem impacts. Biodiversity is related to other measures of ecosystem health including ecosystem services and ecosystem resilience. The term “reduced biodiversity” is assumed to encompass a multitude of the interactions and ecosystem community dynamics that result from the loss of habitat, loss of sensitive species, or increase in less desirable species with specific advantages to better adapt and/or thrive in expected future conditions.

Climate change may dramatically change forested and range landscapes, resulting in expansions of some forest types and the contraction of others (e.g., conversions of woodland to brush and grassland habitats) (CNRA, 2009). Species attributes that will facilitate vegetation distribution changes include broad environmental tolerances, a relatively rapid rate of reproduction, and the ability to disperse to new locations. Slower-growing vegetation communities with limited dispersal capabilities may be outpaced by climatic change (CNRA, 2009). These changes will affect biodiversity via impact habitat availability, quality and connectivity. Increased air temperature could affect plant species behavior, including seed production, seedling establishment, growth, and resilience. It also reduces moisture availability for plants, increases the risk of wildfire, and is likely to enhance the survival and spread of deleterious insects, pathogens and/or diseases (CNRA, 2009).

Disturbance events can benefit invasive species, given their tolerance to a wide range of environmental conditions, and can be an important driver of vegetation change on the landscape (Beaty and Taylor, 2008). Invasive species threaten the diversity or abundance of native species through competition for resources, predation, parasitism, interbreeding with native populations, transmitting diseases, or causing physical or chemical changes to the invaded habitat. Invasive species may be able to exploit temperature or precipitation changes and often have greater flexibility under variable and extreme conditions, such as floods, wildfires, or drought. For example, the combined effects of warming and increased wildfire frequency may lead to a reduction of species dependent on old forest, such as the Northern Spotted Owl (*Strix occidentalis caurina*), and may increase abundance of species dependent on early successional habitat, such as the Northern Pocket Gopher (*Thomomys talpoides*) (McKenzie et al., 2004).

6.3 PHYSICAL SYSTEM: RIPARIAN CORRIDORS AND SEZ

Watershed processes that will affect riparian and SEZ habitats are tightly coupled with climatic forcing, land-use practices, and biogeographic changes (e.g., vegetation succession following wildfires). Riparian corridors and SEZs are likely to be affected by warmer future climate. The future climate and potential hydrologic responses are best expressed as increased relative risk of future trends and frequency of events. Projected hydrologic trends can be used to infer the potential impacts to the riparian corridor and SEZ system. High runoff and flooding episodes may cause more extreme seasonal change to moisture availability and increased soil erosion. Earlier snowmelt, drier summer conditions and increased maximum summer temperatures would increase the risk of stress to riparian species. Table 6.3 details the main potential impacts to the riparian (SEZ) system and below we provide a summary of the potential riparian impacts and examples of local and regional supporting research.

Riparian (SEZ) System Impact	Causal Factors	Examples
Changes in soil moisture dynamics	Increased winter precipitation falling as rain; Higher summer temperatures and greater risk of drought	Reduced summer soil moisture available for riparian species.[22,30]
Increased erosion risk	Increased saturated antecedent conditions and rain on snow events leading to larger peak flows; Increased wildfires	Combined increase of causal factors may result in increased risk of mass wasting, soil erosion and/or channel erosion. [66]
Increased stress on cold water fish species	Increased risk of reduced summer baseflow conditions; Increased water temperatures; Risk of episodic high pollutant loading	20%- 40% reduction the salmonid population by the year 2050.[4] Higher vulnerability of Mountain Yellow-Legged frog species.[97]
Reduced riparian (SEZ) biodiversity	Changes in soil moisture dynamics; Increased frequency and intensity of fires; Seasonal hydrologic changes may alter and reduce habitat quality and quantity for riparian and aquatic species	Increased risk to intolerant species within all riparian flora and fauna community. Loss of riparian species not able to adapt to habitat changes and loss.

Table 6.3. Potential climate change impacts on the riparian (SEZ) system in the Lake Tahoe Basin, including causal factors and examples. *Note: footnotes refer to literature cited in Chapter 8 – References.*

CHANGES IN SOIL MOISTURE DYNAMICS

Expected climate changes are likely to create greater seasonal and inter-annual changes in soil moisture conditions in Lake Tahoe Basin watersheds. These changes are expected to result in relatively wetter soils in the winter season (Dettinger et al., 2009) and drier soils in the summer (Dettinger et al., 2004) compared to the present. Figure 5.5 illustrates the changes in winter soil moisture in the western U.S. in response to potential changes in timing and magnitude of winter peak runoff events and snow melt (discussed in Chapter 5). When soils are already saturated, subsequent runoff events can result in a greater fraction of surface water runoff due to the reduction in the infiltration capacity of the soils. The winter soil moisture increases as a result of less snow and more rain delivery, and the increased frequency of rain on snow events contributes to the predictions of increased peak flows and increased risk of flooding in the future. Conversely, greater potential evaporation and evapotranspiration from soils during summer months (Hayhoe et al., 2004) will create a drier watershed and riparian areas during summer months. The soil and climatic changes may result in decreased summer baseflow in Lake Tahoe Basin streams.

INCREASED EROSION RISK

Climate related wildfire extent and severity increases may decrease hill slope and channel stability, resulting in more frequent and larger mass wasting events such as landslides, debris flows, and slumping. These may increase sediment loading to streams and potentially cause increased erosion within Lake Tahoe watersheds. Mass wasting events can also increase the risk to structures, public safety, integrity of road systems, and other infrastructure. The degree of erosion that may occur as a result of more extreme weather events in specific watersheds will depend on watershed characteristics, such as geology and soil erodibility (Naslas et al., 1994). Thus, the relative sensitivity of increased erosion in streams as a result of climate change is very difficult to predict with any confidence. For example, in the Lake Tahoe Basin, well-forested watersheds on granitic and meta-sedimentary terrain have lower sediment output compared to badland areas originating from volcanic mudflow parent material (Stubblefield et al., 2009). The poorly vegetated, gullied badlands in the upper reaches of Ward Creek (Lake Tahoe Basin, 25 km^2) comprise only 1.2% of the watershed, yet were shown to contribute 10-39% of the snowmelt-derived suspended sediment loads emanating from the watershed (Stubblefield et al., 2009). Low-gradient portions of main channels provide temporary storage for fine sediments until the high flows of the spring snowmelt flush material to Lake Tahoe (Stubblefied et al., 2009). The increased frequency of large floods may increase the erosion rates in the upper reaches of Tahoe Basin watersheds.

INCREASED STRESS ON COLD WATER FISH SPECIES

Future stream conditions may increase stress on cold water fish species if the ecological demand for water exceeds the available amount during a certain period or when water quality factors (e.g. temperature or pollutants) reduce habitat suitability. Additionally, riparian shading, stream morphological characteristics, stochastic disturbance events, and pollutant loading may play an important role for determining habitat suitability (Jager et al., 1999; Williams et al., 2009). Preservation and restoration of habitat that support native species and promote biodiversity may become more critical as less water may be available to support aquatic ecosystems and stream temperatures in summer months may approach the upper limits acceptable for introduced and native fish species. Dunham et al. (2003) note that the negative climate change related impacts on vulnerable fish populations are exacerbated by degradation of cold water fish habitat due to other human impacts in watersheds.

Minimum seasonal flows in streams can limit the available habitat of aquatic species causing a multitude of stress to native and introduced fish species. Reduced stream water depth and higher air temperatures will increase stream water temperatures to levels that are potentially unhealthy for cold water fish, such as introduced salmonid species (Moser et al., 2009). In a recent study two global climate models (both using the “A2” emissions scenario) were used to test how future climate would affect salmon spawning habitat and populations. Model results indicate a 20%- 40% decline in the salmonid population by the year 2050 (Battin et al., 2007). The primary reasons for the population declines were warmer stream temperatures, which reduced suitable cold-water habitat; reduced stream flows for salmon spawning, incubation, and rearing; and damage to salmon eggs from increased winter runoff scouring streambeds (Battin et al., 2007). Stream temperature modeling experiments in the Sierra Nevada by Jager et al. (1999) indicate that changes in temperature and flow regime both influenced simulated persistence of brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykis*s). Their study supported the hypothesis that climate change will restrict trout to higher elevations in the Sierra Nevada.

Climate change may exacerbate declining habitat and population trends for several native fish species, including the Lohontan Cutthroat Trout (LCT) due to warming stream temperatures and increasing disturbance events such as wildfires and floods. Evidence suggests that vulnerability of native fish populations to fire is dependent on the quality of affected habitats, the amount of habitat available, the degree of habitat connectivity, habitat specificity of species, non-native species invasions (Dunham et al., 2003). Disturbance events such as fire and subsequent flooding and erosion events can further restrict the amount of suitable habitat for native coldwater fish (Dunham et al., 1999), may facilitate invasions of non-native fish (Dunham et al., 2003), and can be lethal to at-risk trout populations especially if they are isolated from downstream cohorts and habitats (Burton, 2005). For example, changes in flood magnitudes that can result from fires can create a timing mismatch between the hydrologic regime and spawning behavior (Williams et al., 2009). Extreme erosion events following large fires have been shown to reduce fish abundances between 95-100%, primarily due to low dissolved oxygen levels resulting from sediment inputs and could extirpate entire at-risk fish populations (Lyon and O'Connor, 2008).

REDUCED RIPARIAN (SEZ) BIODIVERSITY

Threats to biodiversity (number and variety of species of plant and animal life within a given region) in aquatic habitats are related to the projected future extreme low-flow and flood events. Riparian vegetation, phytoplankton, fish, amphibians and invertebrate communities are sensitive to changes in streams flows and temperatures. Warmer air and water conditions may create conditions that promote the introduction and spread of undesirable species or diseases. Changes in the seasonal soil moisture dynamics (i.e., increased soil moisture during the winter and decreased soil moisture during the summer) may have significant impacts on the vegetation communities, such as shifts towards more xerophytic vegetation. Species that are not able to adapt to changes in moisture, breeding cycles or disease exposure will be lost from a community. Impacts to individual riparian species are difficult to predict since they will often depend unique characteristics of streams and complex interactions with numerous factors other than changing temperatures (Williams et al., 2009). However, there is sufficient information to infer a number of impacts related to a number of Tahoe Basin species of particular concern.

The potential for native meadow and riparian species to be replaced by those more tolerant to drier summer conditions and climate-induced impacts could be substantial. For example, Quaking Aspen (*Populus tremuloides)* is a water-limited, drought-intolerant species and severe drought may cause the death or decline of tree stands (Hogg et al. 2002). This effect will be counterbalanced by the tendency for more frequent fires to favor aspen regeneration, rather than conifers (Elliot and Baker 2004), and may reverse the natural succession of aspen stands to conifers (Dale et al., 2001). The Tahoe Yellow Cress (*Rorippa subumbellata*) is unique to Lake Tahoe and is listed as endangered by both California and Nevada. Its narrow geographic and ecological ranges combined with observations of how the species is affected by lake level dynamics (BMP Ecosciences, 2008) provide evidence for a potential threat to persistence of the species from climate change impacts.

Amphibians are likely to be more vulnerable to extinction or extirpation in a warmer climate due to UV exposure desiccation, prevalence of diseases, and interaction with physical environmental factors (Kieseker et al., 2001). Because of their permeable skin, biphasic lifecycles and unshelled eggs, amphibians are extremely sensitive to small changes in temperature and moisture (Carey and Alexander, 2003). With drier summer month conditions more prevalent, the persistence of vernal pools, wetlands, and wet soils will decline and they may become less connected (Schindler, 2009). Yellow-Legged Frog populations, which extend into the Tahoe Basin, have been decimated in the past by introduced fish. The study completed by Lacan et al., 2008 provide evidence that the increase in drying of small ponds will severely reduce yellow legged frog (*Rana sierrae*) recruitment in the Sierra Nevada. This species now suffers local extinction and may be further impacted by indirect effects of global warming such as pathogen occurrence (Pounds et al., 2006) and changes in standing leaf litter (Wake, 2007).

Native populations of the endangered (California listed) Willow Flycatcher (*Empidonax traillii*) are among the native bird populations that may be affected by climate change impacts. Recent population decline and range contraction of this species have been primarily ascribed to degradation of its meadow habitat in the Sierra Nevada. Warming temperatures have the potential to shift its ecological range, putting additional stress on the species (Hitch and Leberg, 2007). Warmer temperatures earlier in the year and a reduced snowpack may reduce standing water in meadows in the late summer, which may have important consequences for meadow nesting birds. The fact that extirpation of the species has been reported in Yosemite National Park, where a great deal of habitat protection exists, indicates cause for concern for health of the species in other areas (Siegel, et al., 2008).

STREAM WATER QUALITY PROJECTIONS

In addition to raising stream temperatures, future climate conditions have the potential to degrade water quality conditions in local streams and Lake Tahoe if climate conditions directly or indirectly cause pollutant loads to increase. The historic lowest clarity of Lake Tahoe occurs in years of heavy runoff, when sediment and nutrient inflow to the lake are highest (Jassby et al., 2003). Higher flood peaks will create the potential to mobilize material from areas that have not typically been substantial pollutant sources or increase stream bank erosion rates. They may also amplify contributions from areas that have shown disproportionate loading such as the bare, incised badland areas in the uplands of Ward Valley and Blackwood Canyon (Stubblefield et al., 2009).

Using simulations from the Lake Tahoe Watershed Model developed for the Lake Tahoe TMDL, Riverson (2010) provided a preliminary view of how annual runoff and nutrient and sediment loading from Lake Tahoe watersheds may change in the future under the A2 and B1 climate scenarios (Figure 6.3). Figure 6.3 shows percent pollutant loading relative to a historical baseline. These simulations indicate that annual loads of nitrogen and phosphorus generally correspond to changes in flow over up to the year 2100 under both A2 and B1. Notably, Riverson (2010) reported no reduction or slight increases in sediment loads with reductions in flow from 2033-2099 under the B1 scenario, and slight increases in sediment loads with a reduction of flow during the 2002-2033 period under the A1 scenario (see Figure 6.3). The slight projected increase in future loading is in response to potential increases in streamflow volumes and, as mentioned above, stream channel erosion risk may increase as a result of increase stream discharge conditions. There are numerous limitations with these simulations, including the fact that these simulations do not include factors such as changes in land use, land-use management, or wildfire regimes that are likely to have a strong affect on these processes and, in turn, pollutant transport from watersheds (e.g., Riverson, 2010). Additionally, pollutant loading results are generated from integration of multiple models and multiple assumptions regarding future emissions, climate, and pollutant generation and transport in the Lake Tahoe Basin.

It is reasonable to conclude, based on existing research and information, that watershed water quality may not be as sensitive to climate changes as it is to sustainable land use management practices and pollutant source control actions.

6.4 PHYSICAL SYSTEM: BUILT ENVIRONMENT

The built environment is defined as any feature on the landscape that has direct human value including structures, real estate, roads, bridges, etc. The majority of the built environment in Lake Tahoe Basin is within the urban boundaries, but more dispersed features are present within the forest (e.g., fire roads), riparian (SEZ) (e.g., bridges), and the Lake (e.g., piers). Climate change impacts include increased likelihood of natural disasters such as wildfires, flooding and landslides, which are typically of much greater concern when a feature of the built environment is threatened than when these events occur in undeveloped areas. Wildfires and landslides are discussed in other sections and this section focuses the potential impact of increased flooding (Table 6.4).

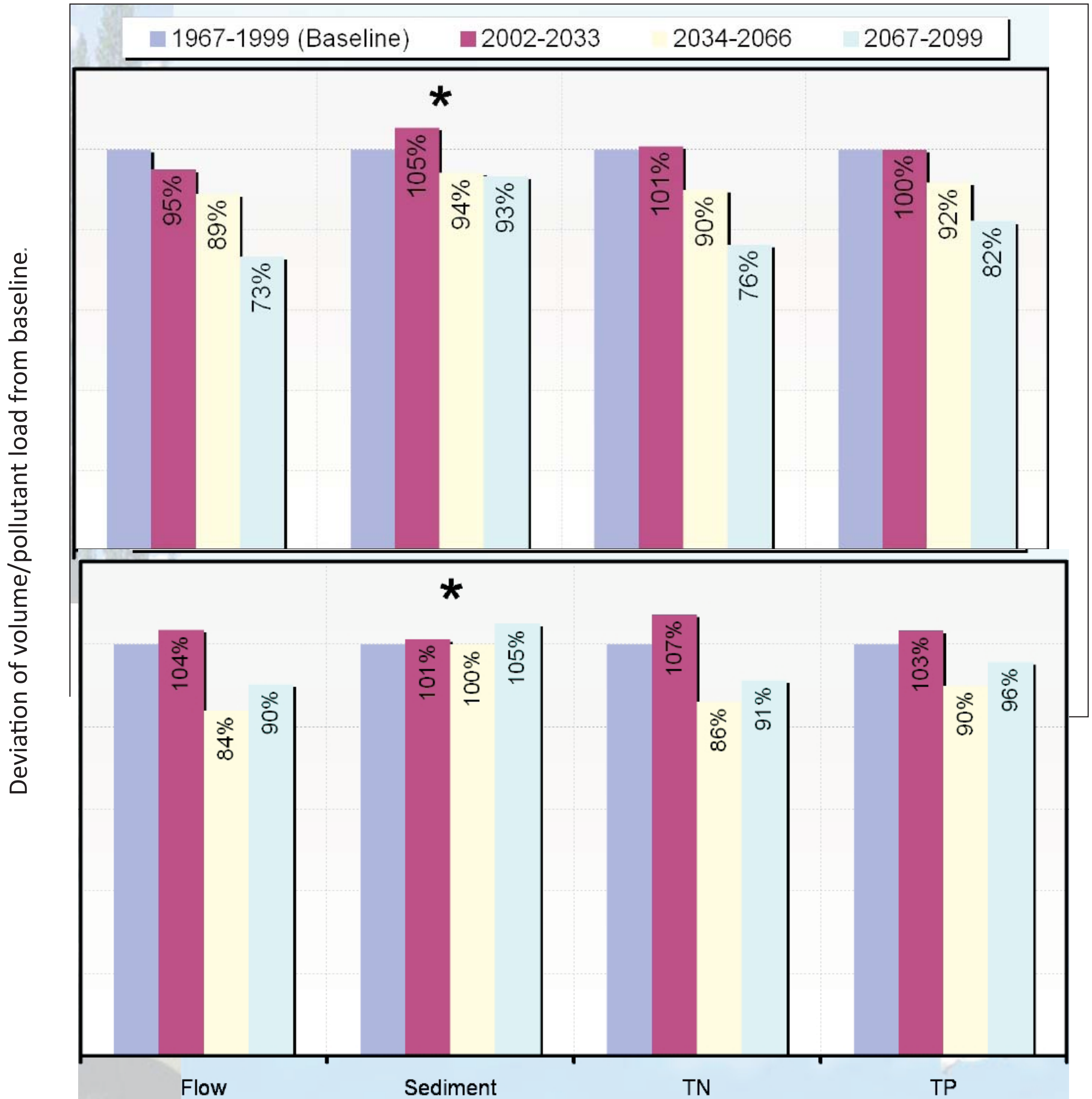
Built Environment System Impact	Causal Factors	Examples
Increased flooding risk	Increased rain versus snow; Increased risk of rain on snow events; Increased winter soil moisture and risk of saturated conditions during large winter rain events	Increased risk to any built systems within the existing 100-yr floodplains. Increased stormwater conveyance challenges during winter months within Lake Tahoe.[16]

Table 6.4. Potential climate change impacts on the built environment in the Lake Tahoe Basin, including causal factors and examples. *Note: footnotes refer to literature cited in Chapter 8 – References.*

INCREASED FLOODING RISK

Climate changes may exacerbate the challenges of stormwater management due to projected changes in flood frequency relationships. Long-term projections for the Lake Tahoe Basin call for little change in total annual precipitation amounts, but the ratio of rain to snowfall is expected to increase. In addition, the risk and associated frequency of rain on snow events is predicted to increase as a result of increased minimum winter air temperatures. Modeling projections previously discussed (see Chapter 5) by Coats et al. (2010b) suggest that the flood frequency curve for the Upper Truckee River will shift upward sharply for the middle third of this century, with the 100-yr expected flood increasing (for the B1 scenario) 2.5-fold (see Figure 5.9). The curve is expected to shift downward again by the end of the century as the snowpack and rain-on-snow events decline. Such hydrologic changes would impact physical, built and human systems. Increased channel erosion, higher flood stages, and undersized stormwater infrastructure are some the issues that Lake Tahoe community will have to address in the future.

Hydrologic analyses completed for public infrastructure and stormwater improvement projects currently utilize historic datasets and/or simple hydrologic regression equations to estimate infrastructure routing and capacity needs. The reliance on these sources of data to estimate hydrologic conditions for Lake Tahoe may not be completely representative of the future 20 to 30 years. While there is a high degree of uncertainty associated with hydrologic predictions, modeling studies are currently the only tools available for estimating future variability that do not depend on the principle that future hydrologic behavior will reflect historic trends. This is important, since historic hydrologic behavior may not be representative of hydrologic behavior in the Lake Tahoe Basin in 20 to 30



Relative changes in flow, sediment, total nitrogen, and total phosphorus loads for the Lake Tahoe Basin from the LSPC watershed model driven by climate projections from the GFDL climate model under the A2 (top) and B1 (bottom) scenarios. Source: Riverson et al., 2010

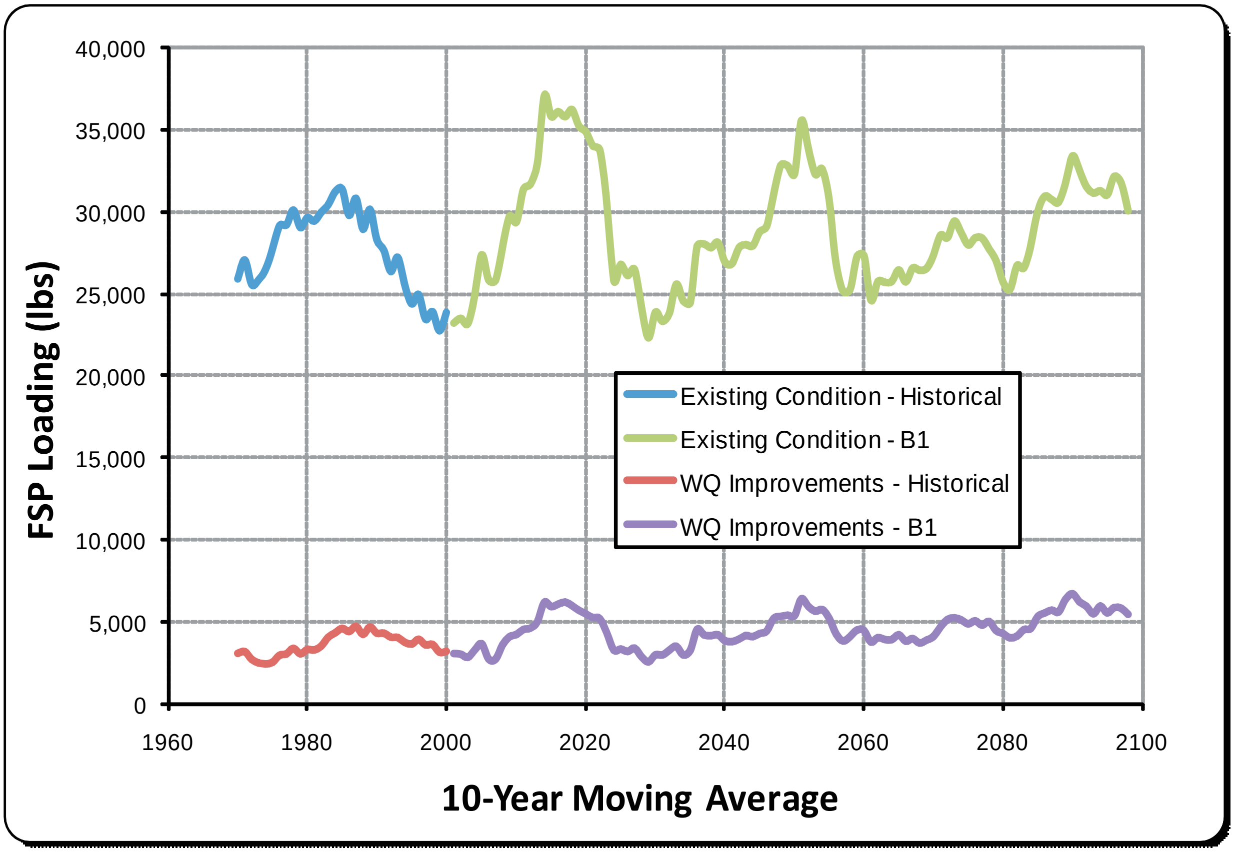
URBAN STORMWATER QUALITY

Future climate changes may exacerbate the widely recognized stormwater pollution problems with which city managers and jurisdictions in the Lake Tahoe Basin are already grappling. Larger flood peaks create the potential to mobilize more material more frequently from city streets and storm drains.

Simulations provided by Coats et al., (2010) provide very compelling evidence that the implementation of identified pollutant reduction opportunities in the urban areas in Tahoe Basin will more than offset the potential increase in water pollution resulting from global climate change. Coats et al., (2010) used the Pollutant Load Reduction Model (PLRM) to predict and compare the potential urban pollutant loading changes as a result of future climatic conditions (A2 and B1 scenarios) in the Lake Tahoe Basin and future land-use conditions after intensive water quality improvements in an urban catchment. The differences in the 10-yr moving average of historic and predicted fine sediment particles (FSP < 16 µm; priority Lake Tahoe pollutant of concern) loading from the Lake Tahoe urban catchment under existing conditions were predicted to be no more than 110% of the 2004 FSP loads. Figure 6.4 illustrates the predicted 5 to 6 fold reduction in average annual FSP loading from the Kings Beach catchment as a result of water quality improvement actions. Given that the most significant source of FSP to Lake Tahoe has been identified as urban roads, the future projected decreases in total annual snowfall will reduce the frequency and magnitude of annual anthropogenic road abrasive applications, thus directly reducing the expected winter FSP concentrations expected on urban roads in the future. These results suggest the urban water quality benefits of water quality improvement actions such as pollutant source control on urban roads, hydrologic source control and stormwater treatment exceed the potential increased water quality threat from global climate change as predicted by the B1 (more moderate) scenario. It is reasonable to conclude based on existing research and information that stormwater quality is not as sensitive to climate change as it is to other controllable factors.

6.5 PHYSICAL SYSTEM: LAKE TAHOE

Lakes act as both integrators of watershed responses to climate change and sentinels of climate change. Williamson et al., (2009) point out the importance of understanding ecological changes in lakes because they provide information-rich signals for how climate is affecting the physical, chemical, and biological systems. As in other lakes around the world, Lake Tahoe integrates the effects of climate responses in its watersheds via sedimentation, providing an integrated record of watershed responses to climatic change. The lake itself may respond rapidly to climate changes, thereby acting as an early indicator of changes to come in other systems (Adrian et al., 2009). The large volume of Lake Tahoe relative to its small drainage area results in a hydraulic residence time of about 650 yrs (Coats et al., 2006). Figure 6.5 illustrates relationships between climate drivers, climate regulators, climate response and forcing, and the physical, chemical, and biological 'sentinel responses' that can be detected in lakes. Physical, chemical, and biological sentinel responses are the clearest indication of changes due to the climate forcing variables of air temperature, precipitation, UV and infrared radiation. The Lake Tahoe system has a number of potential impacts that correspond to the responses illustrated by Williamson et al. (2009) in Figure 6.5. Lake Tahoe impacts associated with future climate change are summarized in Table 6.5.



Comparison of PLRM (nhc et al., 2009) simulation results from Kings Beach urban catchment in the Lake Tahoe Basin. The graphic presents the 10-yr moving average for catchment FSP loading for historical climatic conditions (1961-2000) and projected climatic conditions (2001-2100) using the B1 scenario for existing catchment conditions (2004) and with the implementation of intensive water quality improvement actions. Relative to the FSP load reduction achievable by water quality improvment actions, global climate change appears to have an insignificant impact on urban water quality with respect the Lake Tahoe TMDL pollutant of concern (FSP). Source: Wolfe, 2010

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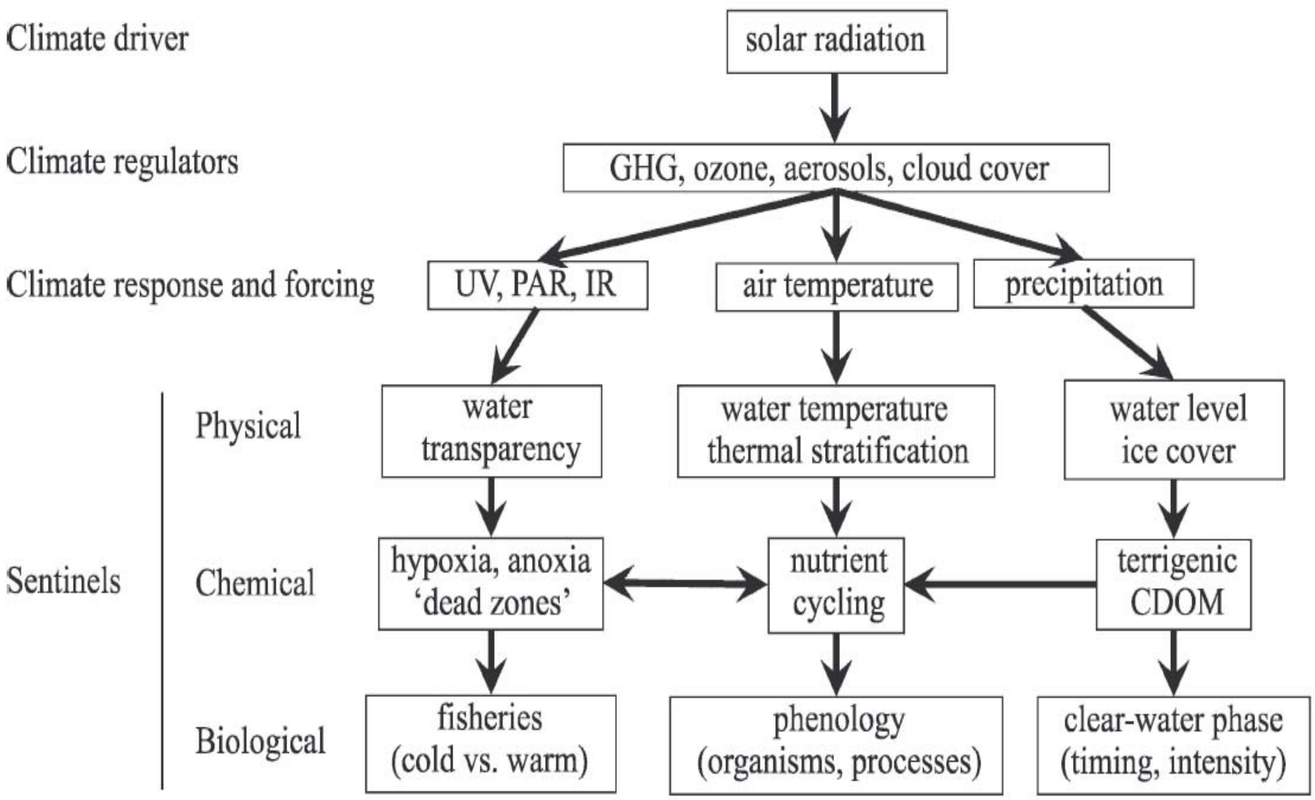
KINGS BEACH PLRM SIMULATION: B1 EMISSIONS SCENARIO VS. INTENSIVE WATER QUALITY IMPROVEMENT ACTIONS

FIGURE 6.4



Schematic diagram showing relationships between climate forcing variables, lake processes, and 'sentinel' responses. Source: Williamson et al., 2009

Lake Tahoe System Impact	Causal Factors	Examples
Reduced frequency of lake water column turnover	Increased lake warming	Persistence of thermal stratification throughout year. Sinking of surface waters and Lake turnover cease.[79]
Increased risk of low dissolved oxygen in deep water column	Reduced frequency of annual lake turnover will reduce supply of oxygen to bottom waters	If lake turnover ceases to occur, the decomposition of organic matter on bottom of the lake may exceed oxygen supply in bottom water. Numerous deleterious water quality and ecological problems could result. [81]
Reduced lake biodiversity	Warming water temperatures; Less mixing; Risk of long-term water quality degradation	Warm water fish species may outcompete coldwater natives.[40] Phytoplankton populations will change.[10]

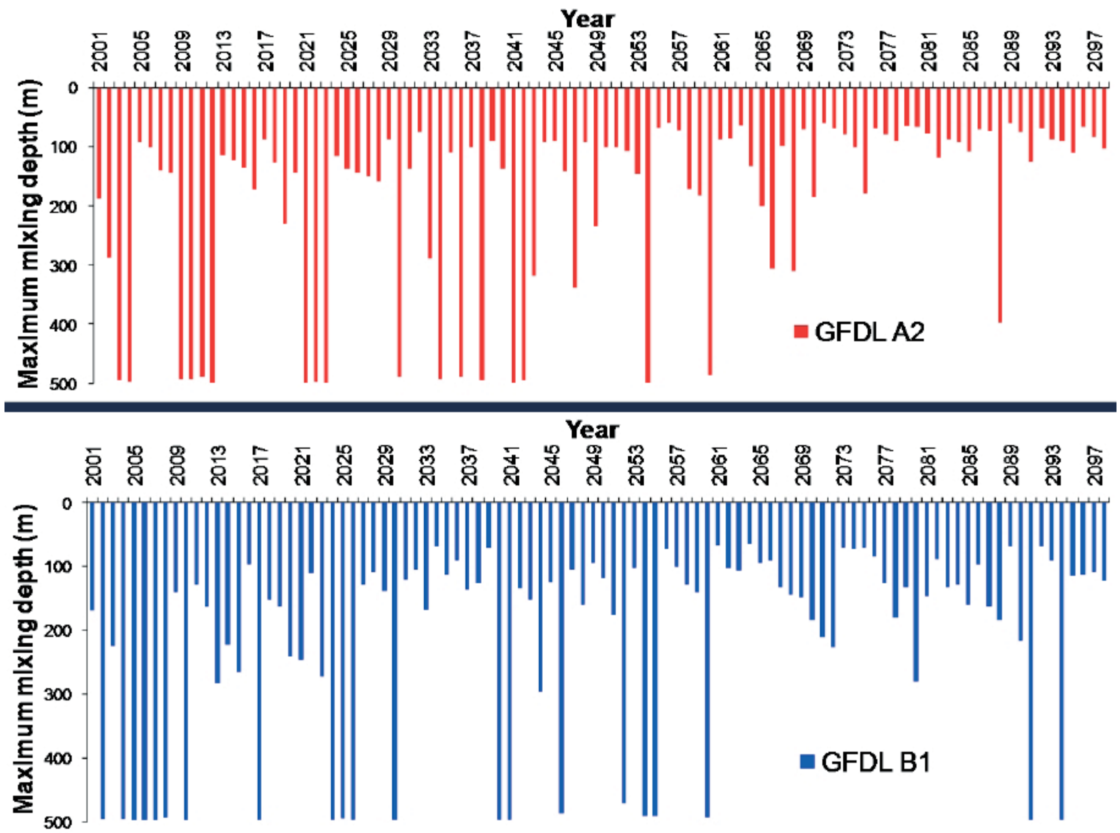
Table 6.5. Potential climate change impacts on the Lake Tahoe system, including causal factors and examples. *Note: footnotes refer to literature cited in Chapter 8 – References.*

REDUCED FREQUENCY OF LAKE WATER COLUMN TURNOVER

Meteorological forces drive the dynamics of Lake Tahoe including heating, cooling, mixing, and circulation (Sahoo and Schladow, 2008). Lake Tahoe is likely to continue the warming trend already observed in the historical data as discussed in Chapter 4. Statistical models indicate that the increase in lake temperature is most closely related to the increase in air temperature, and secondarily to the increase in downward long-wave radiation. Between 1970 and 2007, the lake warmed at an average rate of 0.013 ^{o}C/yr (Coats et al., 2006).

The projected rise temperatures will increase stability of the lake and decrease deep mixing in the future (Sahoo and Schladow, 2008). The depth of episodic mixing in Lake Tahoe can be driven by wind intensity and direction. Complete vertical mixing of Lake Tahoe is controlled by the density difference between the surface and bottom waters. When surface waters cool in the winter their density increases. The sinking of the relatively denser surface waters results in the vertical water column of Lake Tahoe “turning over”. Lake turnover is a valuable process that brings nutrients to the surface and dissolved oxygen to the bottom waters. Historic records indicate Lake Tahoe turns over on average once every 4 years.

Warming is increasing the lake’s thermal stability for two reasons. First, the lake warms from the surface downward, so the Lake surface water warms faster than the deeper water. Second, the decrease in density with temperature (above 4^{o}C) is non-linear. More wind energy is required to mix a stratified lake at 25 ^{o}C and 20 ^{o}C than one stratified at 10 ^{o}C and 5 ^{o}C. Sahoo and Schladow (2008) input GFDL climate model outputs into the Lake Clarity Model and completed simulations extending to 2100. Figure 6.6 shows the maximum annual mixing depths from Lake Clarity Model simulations driven by the GFDL climate model outputs under the B1 and A2 scenarios. Both the B1 and A2 climate scenarios indicate Lake Tahoe’s deep mixing is expected to cease after about 2060. Absence off full mixing for 6 to 10 consecutive years is expected after 2041 (A2 scenario).



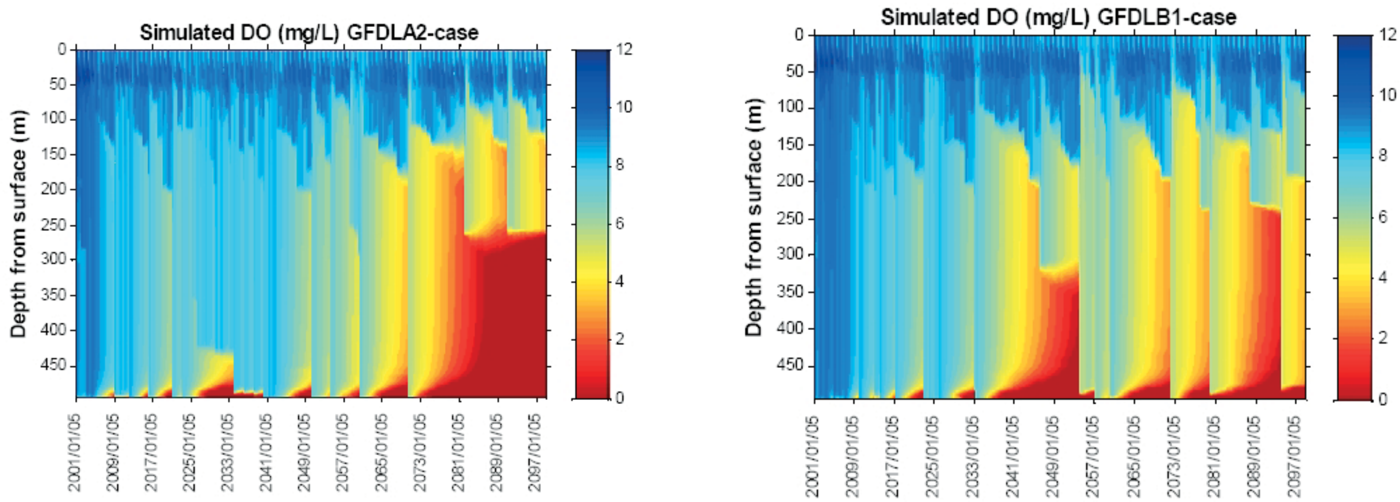
Maximum mixing depths for Lake Tahoe projected to the year 2097 by the Tahoe Lake Clarity Model driven by outputs from the GFDL climate model under the A2 (top) and B1 (bottom) scenarios. Source: Sahoo et al., 2010

INCREASED RISK OF LOW DISSOLVED OXYGEN IN DEEP WATER COLUMN

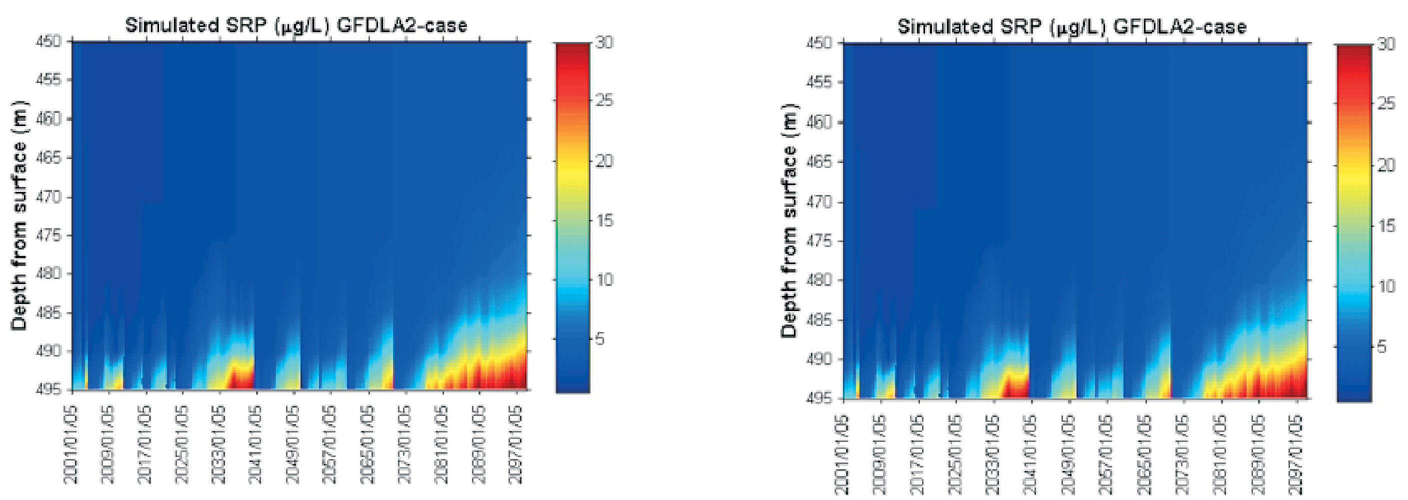
The consequences of increased thermal stability include the potential for prolonged periods of reduced clarity that follow heavy runoff (Coats et al., 2006). Deep mixing moves nutrients from the lake bottom to the water surface, where they promote the growth of algae, and distributes the algae throughout the lake, which supports aquatic life. Conversely, deep mixing moves dissolved oxygen from the surface waters to the bottom waters. If the lack of turnover persists or if turnover ceases completely, then the oxygen demand of the detritus that sinks to the bottom of the lake will exceed the supply of oxygen in the bottom waters. When the oxygen supply is exceeded, anaerobic conditions in the bottom of the lake will develop. The development of anoxic conditions within the bottom waters of Lake Tahoe would have numerous deleterious water quality and ecological impacts. One potential implication of sustained anoxic bottom waters of a stratified aquatic system (such as Lake Tahoe) is the dissolution of soluble reactive phosphorus that is currently locked up in the oxygenated lake-floor sediments (Coats, et al., 2006).

Coats et al. (2010) used the Lake Clarity Model to predict the dissolved oxygen and phosphorous dynamics in Lake Tahoe, should vertical mixing no longer occur in the future. Figure 6.7A illustrates the changes in future Lake vertical dissolved oxygen distributions under the A2 and B1 scenarios. With a prolonged shut-down of deep mixing, anoxic conditions (brown) gradually migrate upward from the sediments. Simulations indicate that the anoxic conditions in the bottom waters will begin to occur intermittently around the year 2020. The simulated progression of soluble reactive phosphorus (SRP) release from lake sediments under the A2 and B1 scenarios up to the year 2097 is illustrated by Figure 6.7B. Substantial SRP release and movement upward in the water column occurs under both scenarios, beginning between 2030 and 2040, and by about 2080, both scenarios indicate sustained concentrations near the Lake bottom as high as 30 µg/L (see Figure 6.7B). Similarly, increased ammonium concentrations above 40 µg/L at the lake bottom will occur for years at a time starting between 2030 and 2040 (Coats et al., 2010). By the year 2100, estimated loading of nutrients to the lake from sediment release is projected to be much larger than loading of nutrients from watershed sources (Coats et al., 2010). In addition to creating a surge in algae growth, bottom anoxia would put severe stress on benthic organisms and fish. In the case of ammonium, the sediment could result in concentrations toxic to many aquatic species in the presence of certain pH conditions.

Ecosystem level responses to climate change such as those reported above are among the most difficult climate change predictions to make with high confidence given the complexity of processes involved and the cumulative uncertainty associated with coupling multiple models together. The predictions above are based on a multitude of interacting models that are built on a number of estimated algorithms and assumptions about lake dynamics, atmospheric interactions (e.g., wind), and ecosystem responses. Considering there are no historic observations of these sustained thermal stratification events (multiple years in duration) in Lake Tahoe, it is difficult to quantify our level of confidence that Lake Tahoe will be a stratified eutrophic anoxic aquatic system by the year 2100. The occurrence of the above described chain of potential impacts will depend on the future rate of climate change, the future minimum winter surface water temperatures of Lake Tahoe, and the future frequency and magnitude of Lake mixing. The actual rate and severity of the potential geochemical implications (anoxia and SRP release) are dependent upon assumptions regarding the dissolved oxygen and other redox element budgets relative to the biological oxygen demand of the sediment and deep waters of Lake Tahoe. However, given these uncertainties, agreement amongst modeling studies clearly indicates a trend towards conditions more likely to produce events leading to water quality degradation of Lake Tahoe in the future. Surface water temperature monitoring and lake circulation dynamics should be tracked and evaluated frequently to continue to evaluate observed changes regularly into the future.



A. Simulated dissolved oxygen distribution in Lake Tahoe up to the year 2097 from the Tahoe Lake Clarity Model driven by outputs from the GFDL climate model under the A2 (left) and B1 (right) scenarios. Source: Sahoo et al., 2010



B. Simulated soluble reactive phosphorus (SRP) distribution in Lake Tahoe up to the year 2097 from the Tahoe Lake Clarity Model driven by outputs from the GFDL climate model under the A2 (right) and B1 (left) scenarios. Source: Sahoo et al., 2010

REDUCED LAKE BIODIVERSITY

As climate and lake dynamics change, freshwater lake species are likely to be more susceptible to local eradication because their habitats may disappear entirely or they may be unable to migrate to a new aquatic environment. Further establishment of warm water fish species threatens to displace and decrease native fish populations in shallow coves and harbors.

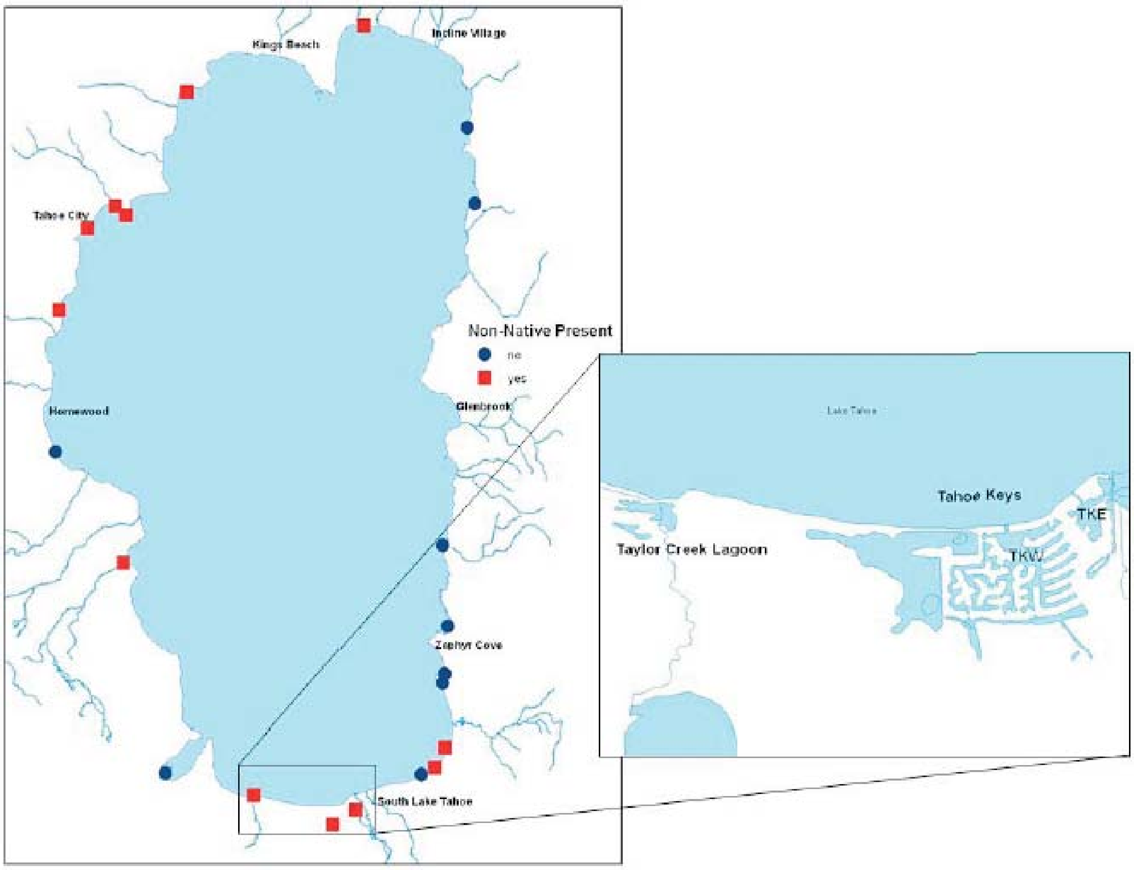
Warming that affects individual species in Lake Tahoe may have profound impacts as changes cascade through the ecosystem with the potential to reduce biodiversity. For example, changes in primary producer species (algae) are crucial for the entire lake ecosystem and are likely to have impacts on higher trophic level organisms. Winder et al., (2004) showed that climate change over the latter part of the 20th century produced a mismatch in the timing of favorable environmental conditions in an algal–herbivore interaction. Such mismatching may have critical consequences for all ecosystems, especially if keystone species are affected. In pelagic ecosystems, algae–zooplankton interactions form the basis for energy flux to higher trophic levels and decoupling of this predator–prey relationship may be transmitted to all trophic levels (Winder et al., 2004).

Climate warming will alter phytoplankton structure and dynamics largely through effects on nutrient availability and sinking velocities (Winder and Hunter, 2008). Among diatoms, the dominant taxonomic group in Lake Tahoe, *Cyclotella* is the only genus that increased significantly over the last few decades. A study by Winder and Hunter (2008) suggests that intensified stratification will provide a competitive advantage to *Cyclotella* in Lake Tahoe due to their small cell size, which reduces sinking velocities and gives them buoyancy at periods of stronger thermal stratifications (Winder and Hunter, 2008).

Fish species are among those that will be affected by environmental changes likely to occur in Lake Tahoe. In recent years there has been an invasion of warm water fishes including Largemouth Bass (*Micropterus salmoides*) and Bluegill (*Lepomis macrochirus*) (Kamerath et al., 2008). Figure 6.8 shows the locations of invasive species detections around Lake Tahoe. It is believed, with the help of climate change increasing lake temperature, these species are spreading to other areas from established populations on the south shore. Figure 6.8 doesn't include anecdotal evidence from CA Department of Parks and Recreation staff that indicates brown bulkhead catfish are present in Emerald Bay the mouth of Eagle Creek. Drier conditions will also result in less chromophoric dissolved organic matter (typically measured as dissolved organic carbon content) entering waterways. This organic matter acts as a 'sunscreen' to UV radiation sensitive species in the lake and streams (Schindler, 2009) and thus controls both the depth of the euphotic zone in lakes, where particulate matter is low, and the depth to which harmful effects of UV can reach. Species that are more resistant to the UV radiation will be in a better position to survive under conditions permitting more UV radiation to penetrate the water column (Schindler, 2009).

6.6 HUMAN SYSTEM: HUMAN WATER SUPPLY

Human systems are a network of programs, issues or resources that are likely to be directly or indirectly influenced by the impacts of climate change on physical systems. Human systems crosscut and rely upon a number of physical systems and components and are typically important to maintain human health and safety. The only human system addressed by this synthesis is water supply. While many other human systems are relevant to climate change impacts, they are outside the scope of this synthesis since they involve substantial socioeconomic and political components. Potential impacts to the water supply system are addressed in a general way that avoids detailed legal and political considerations which will be important for understanding practical implications of changes. Table 6.6 provides the primary impact expected to water supply as a result of future climatic conditions.



Squares indicate that at least one warm water nonnative species was present during at least one snorkel survey period from May to November 2006. Circles indicate that nonnatives were never detected. Source: Kanerath et al., 2007 quality with respect to the Lake Tahoe TMDL pollutants of concern are addressed in physical systems discussed above. Table 6.6 provides the primary impact expected to water supply as a result of potential future climatic conditions.

Lake Tahoe System Impact	Causal Factors	Examples
Increased risk of water use conflicts	Less precipitation delivered as snow; Earlier spring snowmelt; Increased lake evaporation; Less groundwater recharge	Greater risk of necessary trade-offs between using water resources for human consumption and maintaining ecosystem health.

Table 6.6. Potential climate change impacts the human water supply system within the Lake Tahoe Basin, including causal factors and examples.

INCREASED RISK OF WATER USE CONFLICTS

Warmer temperatures will alter the distribution, volume, timing, and type of precipitation, and will also modify the distribution and timing of water needs (CNRA, 2009). Across California anticipated population growth and decreasing reliability of surface water storage as snow will make satisfying the water needs for the state's industrial, urban, agricultural, energy, and environmental uses more difficult (Moser et al., 2009). The Sierra Nevada snowpack is the most important water reservoir in California. The water supply and storage network in California is designed for the current climate conditions with the snowpack providing annual storage and slow spring release and will be less suitable for the new conditions.

Currently, the majority of the Lake Tahoe communities obtain potable water from Lake Tahoe and inflowing streams directly, with the exception of South Lake Tahoe that supplies water primarily via groundwater extractions. The Tahoe City Public Utility District provides water service to the Tahoe City, Tahoe Truckee Forest Tract, Alpine Peaks, Quail Lake/McKinney, and Rubicon areas with 11 surface water storage tanks and a total of 9 groundwater sources, and 2 spring wells (http://www.tahoecitypud.com/utilities/water.shtml). Out of basin exports from Lake Tahoe via the Truckee River provides the primary water source for the Reno-Sparks area.

Warming temperatures will mean the allocation of water for population supply and for ecological services will increasingly come into conflict. Warming temperatures will increase evaporation from the surface of Lake Tahoe and soils, reducing recharge to groundwater aquifers. Modeling studies indicate that Lake Tahoe water surface elevations will increasingly drop below the natural rim for long periods and perhaps permanently (Coats et al., 2010). The shift in precipitation patterns could increase the consumptive use of water for in-basin domestic water supplies and landscape irrigation and out-of-basin water exports via the Truckee River. Additional pressure may be placed on the water supply system from snow making required by ski resorts.

Increased demand for water may affect Lake Tahoe as the goals of maintaining lake levels, supplying industrial and residential land uses, and allowing water release downstream to maintain aquatic ecosystems downstream come into conflict, especially during drought conditions. While there is currently a development moratorium in place in Lake Tahoe, there is no guarantee that it will persist in the future. Regardless, the Lake Tahoe water supply system is bound to experience pressure from development in the future, as there is no such moratorium on development in the Reno-Sparks area whose water supply depends on outlets from the Tahoe Basin. This situation will present a threat to a major part of the water supply in the Truckee River Basin with complex political dimension decisions about water supply policy which may have critical consequences for aquatic ecosystems in the Truckee River and the Lake Tahoe basin.

CHAPTER 7 – APPLICATION OF CLIMATE SCIENCE TO MANAGEMENT ACTIONS

Effective response to climate change impacts will depend on the ability of managers to assess the impacts at relevant spatial and temporal scales, incorporate this information into their decision making process, and develop and implement strategies for adaptation. The magnitude and rate of climate change along with other stressors will be important for determining which systems are able to adapt to changes and which will be more vulnerable. In this section, we describe a framework to assess the level of vulnerability of systems or system components to facilitate selection amongst candidate adaptation strategies.

7.1 VULNERABILITY ASSESSMENT OF CLIMATE CHANGE IMPACTS

An assessment of the vulnerability of a system or system components to changes as a result of future climate conditions provides valuable context of the scientific predictions to guide future management decisions. Systems or system components that are sensitive to climate change and less able to adapt to future climatic conditions are considered more vulnerable to climate change (ICLEI 2007). From a management perspective, the desire is to implement planning actions that reduce the vulnerability of a system to potential future deleterious conditions where feasible. The degree of vulnerability is used to identify system impacts where potential management actions may be able to reduce the vulnerability by strategically increasing our preparation for future impacts. The vulnerability assessment provides a context to focus the discussions of potential adaptation actions that may directly improve our preparedness to climate change.

Borrowing from the ICLEI (2007) climate change guide for local governments, we provide a stepwise vulnerability assessment of potential system impacts to provide managers with a clearer understanding of the combined relative sensitivity and adaptability of Lake Tahoe systems to potential future climatic conditions. Below we define the terms and considerations for evaluating the relative sensitivity, adaptive capacity, and vulnerability of identified Lake Tahoe system impacts as presented in Chapter 6. These definitions are used to provide a preliminary vulnerability assessment of the identified potential future impacts to Lake Tahoe systems related to aquatic resources.

SENSITIVITY

Sensitivity is the degree to which system components (e.g., wildfire regimes, salmonid populations, or stormwater conveyance) respond to climate conditions (e.g., temperature and precipitation) or system impacts (e.g., stream temperature increases or snowmelt timing changes). If the system or system component is likely to be significantly affected by future climatic conditions then it is considered sensitive. Table 7.1 presents the definitions of the relative sensitivity scale. Factors considered when determining the relative degree of sensitivity include:

- The degree of exposure of the impact to climate change. For example, the Lake Tahoe snowpack has a high exposure to climate change.
- The existing stressors in the system and whether future climatic conditions would exacerbate these stressors.
- The existing balance of resource demand and supply such that climate may increase demand and/or reduce supply.
- Are there limiting factors of the system or component that restrict the system's ability to adapt, thus increasing sensitivity? For example, alpine species' ability to adjust to future climate can be limited by elevation if they currently exist at the top of the existing elevations in Lake Tahoe.

Sensitivity	Definition
High	The system responds measurably to an impact based on historical observations or modeling studies.
Moderate	The system response to an impact has not been measured, but based on our understanding system function there are likely to be direct or indirect responses.
Low	The system does not respond measurably to impacts and based on understanding of system function there are not likely to be direct or indirect responses.

Table 7.1. Scoring definitions for sensitivity to climate change impacts.

ADAPTIVE CAPACITY

Evaluating the adaptive capacity of a system is the second step that provides the context of the inherent natural ability of a system or system components to accommodate climate change **without** any human intervention. In determining how adaptive a system is to climate change the following elements are considered:

- Current level of stressors and flexibility to respond to future stressors. Can or has the system component adapted to historic climatic changes or inclement conditions?
- Are there any barriers to the system's abilities to accommodate adjustments (legal, physical, biological) in response to future climate?
- How do timescales of adaptation rate compare to the rate of climate changes?
- Are there efforts currently underway that would increase adaptability (e.g., water conservation)?

Adaptability	Definition
High	The system is expected to accommodate climate changes and expected impacts in ways that avoid negative consequences.
Moderate	The system has some capacity to adjust, and the degree of negative consequences will depend on the magnitude of individual and cumulative impacts.
Low	The system has little or no capacity to accommodate expected impacts so that negative impacts cannot be avoided.

Table 7.2 Scoring definitions for adaptive capacity to climate change impacts.

VULNERABILITY

Vulnerability is the susceptibility of a system component to harmful impacts due to climate change. The vulnerability of systems to specific climate change impacts is determined by combining sensitivity and adaptive capacity scores in the manner outlined in Table 7.3. System components that have high sensitivity to climate changes and a low capacity to adapt are considered to be highly vulnerable to climate changes. As sensitivity decreases the weighting of the adaptive capability is preserved, such that even a system component that is considered not sensitive to climate change but has a low ability to adapt is considered moderately vulnerable.

		Sensitivity		
		High	Moderate	Low
Adaptive Capacity	High	Moderate	Low	Low
	Moderate	High	Moderate	Low
	Low	High	High	Moderate

Table 7.3. Vulnerability ranking matrix.

Our confidence in the vulnerability scores is limited by the available science and body of information used to score sensitivity and adaptability. It must be noted that these determinations for both sensitivity and adaptive capacity are somewhat subjective and depend upon the perspective and information considered. Therefore, our confidence in the vulnerability of each impact is also provided to put bounds on the strength of the conclusions as defined in Table 2.3.

7.2 VULNERABILITY ASSESSMENT OF LAKE TAHOE IMPACTS TO CLIMATE CHANGE

The criteria listed above were used to estimate the vulnerability of Lake Tahoe systems to specific climate change impacts (Table 7.4). The specification of high, moderate, and low sensitivity, adaptability, and vulnerability necessarily included subjective decisions that were often strongly dependent on the availability and accessibility of information. It must be mentioned that typically the system impacts to climate change that are discussed and researched are those that are considered to be moderately to highly sensitive. Very little emphasis or research has been conducted on components of physical or human systems that are not expected to be sensitive to climate change. Thus, the typical global and regional climate change impacts, as well as those presented in Chapter 6 are biased toward components that are expected to be highly sensitive and thus potentially vulnerable. The vulnerability assessment framework will be useful going forward to determine the relevance of potential impacts that are identified by scientists and how they relate to decision making.

Also provided in Table 7.4 in the final assessment evaluation is the response to the question: “Can the expected impact to the system as a result of future climate be lessened by adaptation actions?” Yes, no, and maybe are used to constrain the power of adaptation actions to reduce the vulnerability of the system to the potential climate change impacts. Examples of adaptation actions are provided where relevant. It is implied that all mitigation measures that reduce emissions will reduce the potential climatic changes predicted in the future and therefore the associated system responses.

Levels of vulnerability are anticipated to change over time as more monitoring data are accumulated and synthesized to identify long-term trends; new science becomes available; adaptation actions are implemented; and demand on resources increases with population growth. Table 7.4 should be augmented and updated in the future as the field of climate change adaptation improves and system-specific experts become more involved in the process.

Table 7.4. Summary of stressors and estimated sensitivity, adaptive capacity, and vulnerability of systems to climate change impacts. Adaptive capacity here is defined as natural adaptability if no human actions, management or policy changes are made.

System	Current and expected stressors	Relevant projected changes in climate/ hydrologic conditions	Projected change in stressors	Expected impacts	Degree of sensitivity to impact	Degree of adaptive capacity to impact	Degree of vulnerability to impact	Vulnerability assessment confidence	Can the expected impact to system be lessened by adaptation action(s)?
Forest	Urban encroachment, human ignition of fires, seasonal moisture stress, invasive insects	Temperature increase, longer/drier growing season, earlier peak runoff, less precipitation as snow	Human wildfire ignitions and urban encroachment into forests may increase with population growth and future development, temperatures more accommodating to invasive insects	Increased risk of wildfire frequency, extent, intensity	High	Moderate	High	Moderate	*Yes* Example: Fuels reduction, public education and policy change (e.g. building codes)
				Shift in the distribution and range of forest flora and fauna	High	Moderate	High	High	*Maybe* Example: Increase habitat connectivity
				Increased tree mortality rates	High	Low	High	Low	*Yes* Example: forest thinning to reduce bark-beetle tree induced mortality
				Reduced forest biodiversity	High	Moderate	High	Low	*Unknown* Multiple non-climatic factors and interactions influence biodiversity
Riparian (SEZ)	Habitat loss, water quality degradation, water usage, disturbance mediated introduced species	Higher peak flows, more frequent flooding, and wetter winter soils, extended drought	All stressors likely to increase with population growth and future development	Changes in soil moisture dynamics	High	Low	High	High	*Maybe* Example: Maximize groundwater recharge
				Increased erosion risk	High	Moderate	High	Low	*Yes* Example: Protect banks; Restore channels
				Increased stress on coldwater species	High	Low	High	High	*Maybe* Example: Maximize groundwater recharge

System	Current and expected stressors	Relevant projected changes in climate/ hydrologic conditions	Projected change in stressors	Expected impacts	Degree of sensitivity to impact	Degree of adaptive capacity to impact	Degree of vulnerability to impact	Vulnerability assessment confidence	Can the expected impact to system be lessened by adaptation action(s)?
Riparian (SEZ)				Reduced riparian (SEZ) biodiversity	High	Moderate	High	Low	*Unknown* Multiple non-climatic factors and interactions influence biodiversity
Built environment	Increasing water and energy needs, aging infrastructure, flooding, wildfire damage to structures, mass wasting damage to structures	Temperature increases, drier summer conditions, less precipitation as snow	Projected climate changes will exacerbate existing problems	Increased flooding risk	High	Low	High	Moderate	*Yes* Example: Improve infrastructure
			Stormwater quality may be more sensitive to source control and treatment than to future climate changes	Degraded stormwater quality	Low	Moderate	Low	High	n/a
Lake Tahoe	Infrequent deep mixing, low lake bottom dissolved oxygen levels, wetland habitat loss, water pollution	Lake temperature increase	Continued lake warming, cessation of full mixing by 2060, potential increase of episodic pollutant loading, increased nitrogen deposition	Reduced frequency of lake water column turnover	High	Low	High	High	*No*
				Increased risk of low dissolved oxygen in deep water column	High	Low	High	High	*Maybe* Example: Reduce loading of limiting nutrient (P species) to lake
				Reduced lake biodiversity	Uncertain	Uncertain	Uncertain	Moderate	*Unknown* Multiple non-climatic factors and interactions influence biodiversity
Water Supply	Competing water uses, drought, water pollution, aging infrastructure	Drier summer conditions, less precipitation as snow, earlier snowmelt	Increased risk of drought	Increased risk of water use conflicts	High	Low	High	High	*Yes* Example: Conserve water; maximize groundwater recharge; reservoir reoperation

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