Climate Variability and Change in Mountain Environments: Some Implications for Water Resources and Water Quality in the Sierra Nevada (USA)

Mariza Costa-Cabral[(a)1], Robert Coats[(b,c)], John Reuter[(c,e)], John Riverson[(f)], Goloka Sahoo[(c,g)], Geoffrey Schladow[(c,g)], Brent Wolfe[(h)], Sujoy B. Roy[(d)], and Limin Chen[(d)]

(a) Hydrology Futures, LLC, Seattle WA. (b) Hydroikos Ltd., Berkeley CA. (c) Tahoe Environmental Research Center, University of California, Davis CA. (d) Tetra Tech, Inc., R&D, Lafayette CA. (e) Department of Environmental Science & Policy, University of California, Davis CA. (f) Tetra Tech, Inc., Fairfax VA. (g) Department of Civil & Environmental Engineering, University of California, Davis CA. (h) Northwest Hydraulic Consultants, South Lake Tahoe CA.

Abstract. This article introduces this special journal issue on climate change impacts on Sierra Nevada water resources and provides a critical summary of major findings and questions that remain open, representing future research opportunities. Some of these questions are long standing, while others emerge from the new research reported in the eight research papers in this special issue. Six of the papers study Eastern Sierra watersheds, which have been under-represented in the recent literature. One of those papers presents hydrologic projections for Owens Valley, benefiting from multi-decadal streamflow records made available by the Los Angeles Department of Water and Power for hydrologic model calibration. Taken together, the eight research papers present an image of localized climatic and hydrologic specificity that allows few region-wide conclusions. A source of uncertainty across these studies concerns the inability of the (statistically downscaled) global climate model results that were used to adequately project future changes in key processes including (among others) the precipitation distribution with altitude. Greater availability of regional climate model results in the future will provide research opportunities to project altitudinal shifts in snowfall and rainfall, with important implications to snowmelt timing, streamflow temperatures, and the Eastern Sierra's precipitation-shadow effect.

1. Introduction

Eight research papers in this special journal issue address climate change in the Sierra Nevada and its impacts on water resources (Figure 1). This introductory article reviews the climate projections used in five of the papers, summarizes papers' goals and methodology, provides background on the Eastern Sierra watersheds that are the topic of six papers, and highlights selected findings. We also suggest several questions that remain open – some old, some that emerge from the new research – representing opportunities for future research.

[1] Corresponding author: Hydrology Futures, LLC; cabral@hydrologyfutures.com

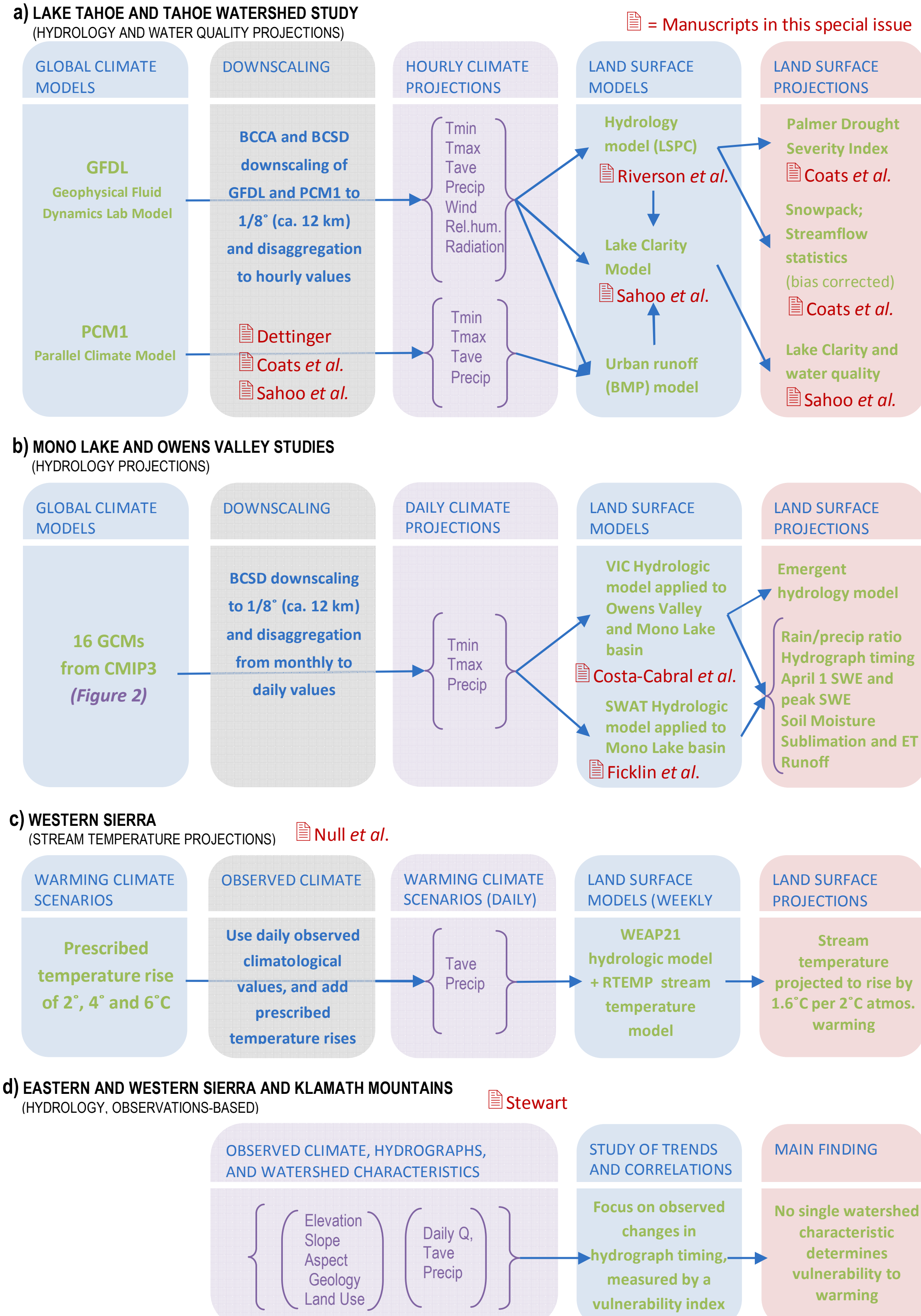

Figure 1. Methodologies of the eight research papers (in red) in this special journal issue.

The six Eastern Sierra papers stem from three projects – the Tahoe project (Figure 1a), the Mono-Owens project (Figure 1b) and the Mono Lake project (also in Figure 1b) – which were separate and independent and had distinct goals. They were not, *a priori*, intended to be complementary, and direct comparisons between them are not always possible.

Across the North American West, some three-quarters of annual runoff originate from snowmelt (Serreze et al. 1999). The Sierra Nevada's snowpack has permitted the growth and development of California's populous cities and large economy, sustains irrigation in the Central Valley's globally important agricultural region, and sustains a unique ecology (e.g., SNEP 1996). The snowpack's response to future climate change will potentially affect every aspect of human life and ecology in the region and have appreciable global impact.

2. Climate Projections for the 21st Century

Five research papers in this special journal issue focus on Eastern Sierra watersheds, using statistically downscaled climate projections from global climate models (GCM) that integrated the Fourth Assessment report of the Intergovernmental Panel on Climate Change (IPCC 2007). In these papers, for each GCM, two contrasting scenarios of future greenhouse gas emissions were used in each study, A2 and B1 (Nakicenovic et al. 2000). Scenarios A2 and B1 respectively lead to 830 and 550 ppmv of CO_2 by year 2100. Scenario A2 presents a world with uneven economic growth and large income gaps between industrialized and developing world regions, where people, ideas and capital have limited mobility, and where technology diffuses more slowly (Cayan et al. 2009). A2 is the highest emission scenario for which most modeling groups have completed simulations, and in most studies represents the highest emissions scenario studied. Although A2 does not represent the highest CO_2 emissions among the SRES scenarios (at least through year 2100), the 21st century emissions to date already appear to surpass A2 (Raupach et al. 2007; Manning et al. 2010). B1 envisions a world with a high level of environmental and social consciousness and a globally coherent approach to more sustainable development (Cayan et al. 2009). B1 often represents the best-case scenario in climate change impact studies. These two scenarios differ little up until the middle of the 21st century, and diverge significantly from there onward (see, e.g., Figure 1 in Raupach et al. 2007).

In this special issue, the studies for Mono Lake and Owens Valley considered 16 GCMs (in Figure 2 legend and *Online Resource*), using daily precipitation and temperature values downscaled to 1/8° spatial resolution by the statistical technique Bias Correction and Spatial Disaggregation (BCSD; Wood et al. 2002; Maurer et al. 2007). The studies for Lake Tahoe and its watershed required additional meteorological variables – wind, relative humidity and solar radiation –, and used a combination of two downscaling techniques: Bias Correction and Constructed Analogues (BCCA; as described in Dettinger 2012, this special issue), and BCSD (as described in Coats et al. and Sahoo et al. 2012, this special issue). Data availability limited the choice of GCMs to two: PCM1 and GFDL-CM2.0.

All 16 GCMs project a rise in mean annual temperature, but they differ in the sign of their precipitation projections for a fixed location (Figure 2), reflecting this variable's sensitivity to process representation in the models. For both time horizons in Figure 2, 15 of the GCMs project precipitation changes within the range [-25%, +25%], while IPSL projects large increases under scenario A2, reaching about +60% for Mono Lake and +70% for Lake Tahoe by end of century. Six of the 16 GCMs project a shift in the timing of precipitation to earlier dates, by about 1 to 2 weeks (see Figure 2 of the accompanying paper by Costa-Cabral et al. 2012, this special issue). With regard to temperature, projected seasonal changes are for faster warming in the period May–September, although for the Eastern Sierra study areas the 16-GCM average projects only about 0.5˚C higher warming in that period than in the rest of the year, for either scenario A2 or B1.

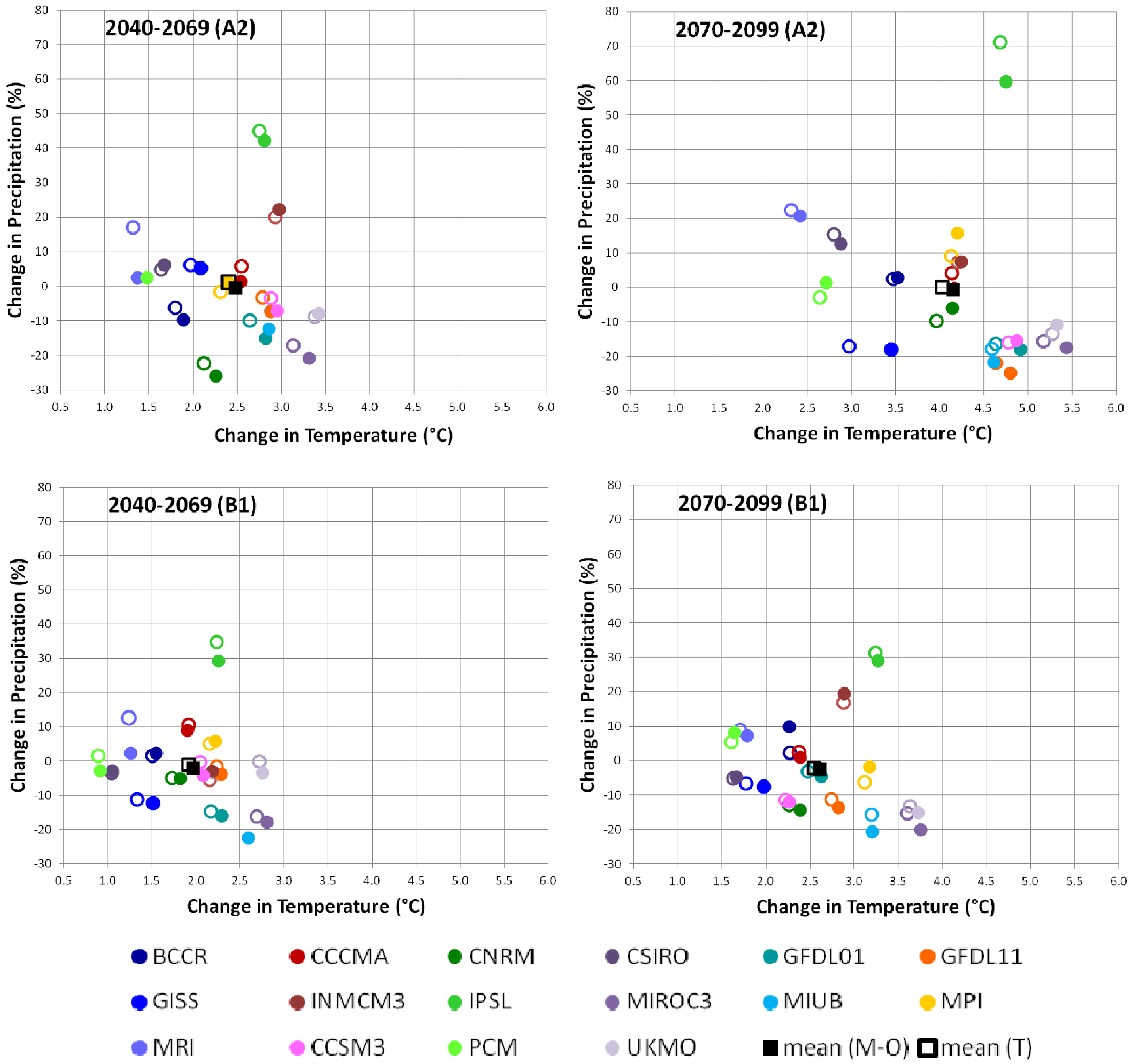

Figure 2. Change in mean annual temperature and precipitation for the mid century period (2040-2066) and end of century period (2070-2099) projected by 16 GCMs and two greenhouse emissions scenarios, statistically downscaled to the location of Mono Lake (filled circles) and Lake Tahoe (open circles). Model means are represented by squares for Mono Lake (filled squares) and Lake Tahoe (open squares). For any given model, projections for the two lakes differ mildly, with a tendency for slightly greater warming and slightly smaller increases or greater declines in precipitation for Mono Lake relative to Lake Tahoe. The data plotted are from Maurer et al. (2007).

The projections shown in Figure 2 and used as future scenarios in the research papers in this special issue are subject to large and unquantifiable uncertainty. The main sources of uncertainty are 1) unknown future emissions of greenhouse gases; 2) uncertain response of the global climate system to rising greenhouse gas concentrations; 3) incomplete understanding of manifestation on regional climate; and 4) uncertain regional hydrologic impacts. The first two are the largest sources of uncertainty at the global scale, and are thought to be of comparable magnitude (Karl and Trenberth 2003). In the case of the Sierra Nevada, (3) is also a major source of uncertainty. The Eastern Sierra research papers use two contrasting greenhouse gas emissions scenarios, B1 and A2 (see above) to partially account for the first concern. The use of many GCMs in some of the studies is also intended to reduce uncertainty as different GCMs exhibit a range of region-specific sensitivity to changing emissions scenarios. However, the true climatic response of the complex and chaotic climate system may lie outside of the realm of GCM results. Thus, the projections in our studies are best viewed as plausible future scenarios of climate and hydrology, and actual future conditions will differ from any of these scenarios. Given the complexity of the physical processes involved in generating precipitation and determining precipitation intensity and totals, which include processes at all scales including local scales, and given that the coarse scale used by GCMs, and even RCMs, their projections for precipitation are understood to be more uncertain than for temperature.

3. The Eastern Sierra Study Areas of Lake Tahoe, Mono Lake and Owens Valley

The Eastern Sierra study areas (Figure 3) represent significant ecological, hydrologic, cultural, and economic resources. The ecological importance of Lake Tahoe and Mono Lake, in particular, has been recognized in major legal protections. They are the only two California water bodies classified as "Outstanding National Resource Water" (ONRW) under the federal Clean Water Act. In the face of climate warming, of particular concern for both lakes are changes in volume (surface elevation and area), thermal stratification, and the consequent changes in the vertical distribution of water quality parameters affecting aquatic life.

3.1 Lake Tahoe and the Tahoe Basin

Lake Tahoe is renowned worldwide for its beauty, clarity and ultraoligotrophic status. An environmental improvement program, involving local, state, and federal authorities has been active for decades, and a Total Maximum Daily Load (TMDL) program for nutrient and fine sediment control was recently approved. Long-term monitoring of Lake Tahoe has documented unfavorable changes (Goldman 2000; Jassby et al. 1999), including *a)* a decline in Secchi depth transparency by 10 m since 1968 (from an estimated historical value of 31 m), *b)* an increase, at about 5% per year, in the rate of ^{14}C primary productivity, and *c)* thick growths of attached algae that now cover portions of the once-pristine shoreline (TERC 2011). Additionally, like many lakes world-wide, Lake Tahoe has been affected by non-native fish and invertebrates that were either intentionally introduced or were part of a large pattern of regional invasion. Some of these are favored by warmer water temperatures (Kamerath et al. 2008; Wittmann et al. 2008). Table 1 specifies some of the characteristics of the Lake and its watershed.

Table 1: Characteristics of Lake Tahoe

Volume =	156 km^3
Surface Area =	498 km^2
Average Depth =	313 m
Basin Area =	1310 km^2
Lake Elevation =	1898 m
Max. basin elevation =	3317 m
Mean Hydraul. Res. Time =	650 yr
Mean ann. Lake discharge =	200 million m^3
Mixes below 450 m about 1 yr in 4	
Well-oxygenated to bottom	
Decline in clarity related to both fine sediment and increasing Primary Productivity (PP)	
PP now controlled by available phosphorus	

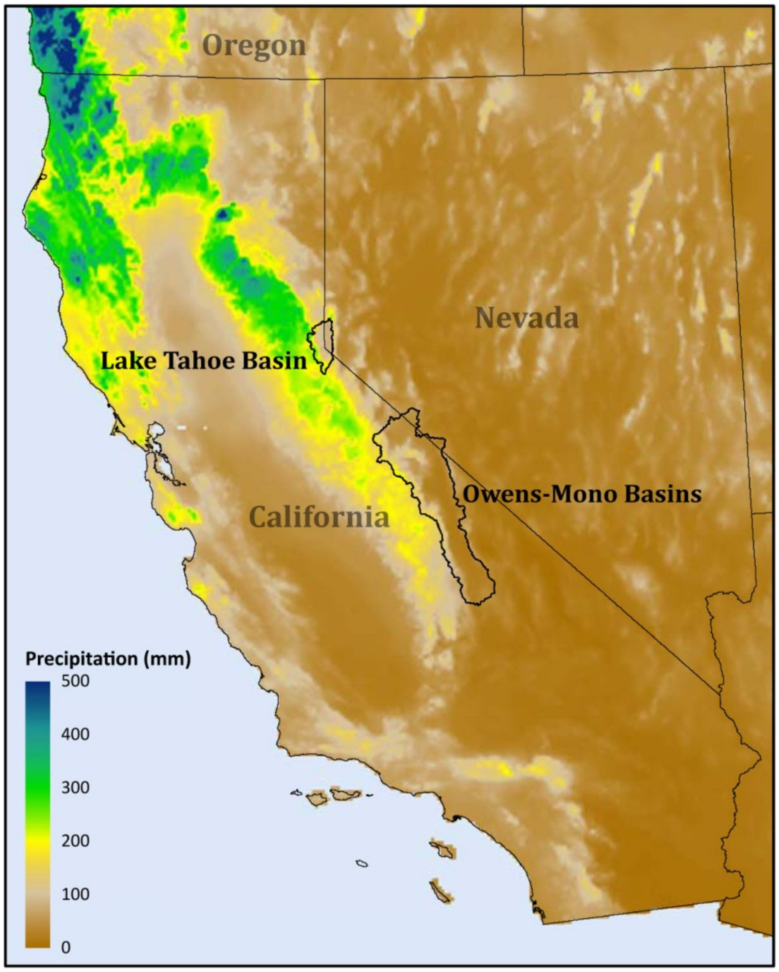

Figure 3. Map of mean annual precipitation in the historical period and indication of the Eastern Sierra Nevada study areas: the Lake Tahoe watershed and the Owens-Mono watersheds.

A complete understanding of the historic and likely future conditions of Lake Tahoe requires consideration of the input of water, nutrients and sediment, and knowledge of those factors that will affect deep mixing (e.g. water temperature, density and wind energy). Work on recent hydroclimatological trends indicated strong increases in air temperature (especially night-time temperatures), a rise in the rain-to-snow ratio, earlier snowmelt timing, increased rainfall intensity, increased interannual variability of precipitation, and a rise in the lake's water temperature (Coats et al. 2006; Coats 2010). Sahoo and Schladow (2008) and Sahoo et al. (2010b) reported on initial attempts to model changes in lake mixing based on coarse-scaled future meteorological conditions.

Coats et al. (2006) showed that Lake Tahoe's water has been warming since at least 1970, and that the warming trend is increasing the lake's thermal stability and resistance to vertical mixing. They hypothesized that with continued warming the reduced mixing would eventually suppress deep-water ventilation, reduce dissolved oxygen in the hypolimnion, and trigger release of available P and ammonium N from the lake bed.

The clarity of Lake Tahoe is threatened by the influx of phosphorus (P) and nitrogen (N), which promote algal growth, and by fine sediment particles (<16 μm) (Swift et al. 2006; Lahontan and NDEP 2010; Sahoo et al. 2010a). These pollutants originate from land disturbance, urbanization and roadways, and inputs to the lake are exacerbated by a loss of natural landscape capable of treating runoff (Coats et al. 2008). Fine sediment particles are primarily of urban origin (an estimated 72%), while an estimated 55% of the N enters the lake via direct atmospheric deposition. Surface runoff from the urban and non-urban portions of the landscape accounts for 39% and 26% of the P load, respectively (Lahontan and NDEP 2010). The Lake Clarity Model (Sahoo et al. 2010a) shows that the transparency standard of 30 m (Secchi depth) can be achieved with a 55% reduction in nutrients and particles from all sources, or with a 75% reduction from urban sources alone.

In most years, Lake Tahoe drains into the Truckee River, supplying water to municipal and agricultural users downstream and helping to maintain adequate conditions in Pyramid Lake at the river's terminus. From 1910 to 2010, the Tahoe basin contributed on average 23% (ranging from 0 to 40%) of the annual yield of the Truckee River at Farad. In 20 out of the last 110 years, however, the lake level has fallen below the rim. If climate change increases the frequency or persistence of below-rim levels, the consequences for water supply in the Truckee River basin could be severe.

Four research papers in this special issue report on the results of a "Tahoe project" (Figure 1a) whose project goals are 1) to provide water resource agencies and decision-makers with a scientific assessment of the importance of incorporating scenarios of future climate change impacts into ongoing efforts to protect the Lake; and 2) to provide a comprehensive evaluation of the potential impacts of climate change to a variety of different yet interdependent aspects of water resources, including local meteorology, hydrology, nutrient and sediment loading, effectiveness of best management practices for load reduction, lake mixing, water quality and water supply.

For development of the Total Maximum Daily Load (TMDL) allocations for the Tahoe Basin, the Load Simulation Program in C++ (LSPC) model was customized for Lake Tahoe basin hydrology (Tetra Tech 2010) to create the Lake Tahoe Watershed Model. This watershed model uses local weather data as the forcing factor, and represents land use coverage, elevation, slope, and soils. The model simulates hourly stream discharge and water quality, including loads for ammonia, nitrate, total N, dissolved P, and total P. The UC Davis Dynamic Lake Model (DLM) coupled with the Water Quality Model (DLM-WQ) constitutes the Lake Clarity Model that was developed and used as part of the Total Maximum Daily Load (TMDL) program to meet regulatory water quality requirements (Sahoo et al. 2010a; Sahoo et al.

2012, this special issue). DLM-WQ is a complex system of sub-models including the hydrodynamic sub-model, ecological sub-model, water quality sub-model, particle sub-model and optical sub-model. The implications of climate change for the design of water quality BMPs were analyzed (Wolfe 2010). For the Lake Tahoe TMDL, a customized version of EPA's Storm Water Management Model (SWMM) was developed to analyze the reduction in pollutant loads associated with specific BMPs and sets of BMPs (Lahontan and NDEP 2010; Wolfe 2010). This model was used to compare the effectiveness of a given BMP design with and without the increased magnitude and frequency of runoff that may result from climate change.

Riverson et al. (2012, this special issue) used GCM-projected 21st Century climatology to force the Lake Tahoe Watershed Model. Coats et al. (2012, this special issue) used the model results to characterize the watershed's hydrologic response to projected climate change. Sahoo et al. (2012, this special issue) used the simulated watershed outputs as inputs to DLM-WQ to explore impacts on the lake's water quality.

3.2 The Watersheds of Owens Valley and Mono Lake

Over four million people in the Los Angeles metropolitan area, and the City's large economy, rely on these watersheds' snowpack as one of their principal water sources, and the one of highest quality. Some 200-500 thousand acre-feet (roughly, 0.25-0.60 km^3) of water are brought annually to the city by the 550 km aqueducts, along which seven reservoirs have a combined storage capacity of about 300 thousand acre-feet (0.37 km^3). The ecological value of the region's water resources reflects the uniqueness of the Mono Lake chemical environment and ecosystem.

Mono Lake has been awarded "mitigation and flow enhancements allocations" that amount to nearly one-half of the historical water supplies from the Eastern Sierra to the Los Angeles aqueducts – thus reducing the aqueducts' average contribution to the city from a historical two-thirds to about one-third of total. Withdrawals for the aqueducts in 1941-1982 contributed to a lake surface drop of 14 m with elevated alkalinity and salinity. Mono Lake's unique habitat nurtures brine shrimp and alkali flies, and is critically important to nesting gulls and migrating grebes and phalaropes (Hart 1996).

The studies reported by Costa-Cabral et al. and by Ficklin et al. in this special issue (see Figure 1b) are separate and independent, having used the same scenarios of future climate (Section 2) but different hydrologic models. The two studies also differ in the extent of the study area. Ficklin et al. investigate the main contributing watersheds to Mono Lake, while Costa-Cabral et al.'s paper also includes all creeks on the Sierra's eastern slope draining into Owens Valley. The hydrologic models were calibrated for Owen's Valley based on discharge data records provided by LADWP extending back to 1950, and were used to obtain 21st Century projections of snow water equivalent, sublimation and evapo-transpiration, runoff, and hydrograph timing. The two studies reach broadly similar conclusions regarding the direction of future changes in winter snowpack accumulation, and snowmelt runoff and its timing (section 4).

4. Major Findings and Open Questions

Taken together, the eight research papers in this special issue offer new insights into the Sierra's climatic and hydrologic diversity, while raising new questions (and old questions anew) to be addressed by future research.

Stewart (2012, this special issue) analyzed the historical climatic and hydrologic records for 1948-2009 to evaluate river basin runoff sensitivity to climate variability and change over a broad region spanning much of California and the western edge of Nevada. A significant trend towards higher mean annual air temperatures was found throughout the region. Additional analysis will be required to determine whether computed precipitation trends, which are positive for some gauges and negative for others (shown in Online Resource 2 of Stewart's paper), are consistent with a dependence on elevation, and whether they may reveal a distinction between eastern versus western slopes. We note that all Eastern Sierra gauges analyzed have positive computed precipitation trends. Statistical significance for precipitation trends is difficult to obtain due to the high temporal variability of precipitation in the Sierra Nevada, at inter-annual and multi-annual scales.

Stewart used the hydrograph center timing (CT) as a measure of sensitivity to the observed regional warming. Figure 1b in Stewart's paper shows that for most (but not all, as noted below) stream gauges there are significant computed CT trends towards earlier dates. Previous research in the Sierra Nevada and throughout the western U.S. (literature references given in *online suppl. mat*.) documented observations of a partial transition from snow to rain, especially marked at elevations just above the previous snow line and a shift to earlier timing of snowmelt (by 5 to 30 days). For most stream gauge stations, this is accompanied by a shift in the observed CT to earlier dates.

Stewart's paper (Figure 1b) shows CT shifts toward later rather than earlier timing for some stream gauges (7 of the 52 snowmelt-dominated, and 9 of the 29 rain-dominated gauges). The reason is unknown and, to our knowledge, this result has not been replicated by any hydrologic simulation of these watersheds. Stewart did not find definite explanatory factors among those studied (elevation, slope, aspect, geology and land use). Hypothetical explanations include *(i)* computational artifacts derived from unrelated factors known to influence CT values (Jessica Lundquist, *pers. comm.*), such as large precipitation episodes occurring in autumn early in the time series, or large late-winter precipitation events occurring in years late in the time series; *(ii)* true trends in the timing of precipitation itself influencing the rain-dominated gauges; and *(iii)* changes in the local orographic precipitation gradient influencing the snow-dominated gauges. These hypothetical explanations have not been tested and represent a future research opportunity.

Previous research has reported an observed decline in snow water equivalent (SWE) at moderately high elevations such as the northern Sierra Nevada, but at the highest elevations in the southern Sierra Nevada a rising SWE trend was reported instead (literature references given in *online suppl. mat.*). The MODIS satellite observational record of fractional snow covered area, initiated in year 2000, is as yet too short to provide sufficient observational evidence on hypothetical elevation-dependent snowpack changes.

Lundquist and Cayan (2007), on the basis of Reanalysis data for 1948-2005, documented a weakening trend in westerly wind speeds. An intriguing possibility worthy of future research (suggested by Jessica Lundquist, *pers. comm.*) is that weakening westerlies may lead to a growing distinction between Western and Eastern Sierra Nevada in terms of temperature, precipitation, and hydrograph timing.

Evidence of a recent growing distinction in temperature trends between Western and Eastern Sierra locations was given in Figure 11 of Lundquist and Cayan (2007). Such changes in atmospheric circulation may have implications to precipitation in the Sierra. Weaker westerly wind speeds often correspond to a higher altitude of the Sierra barrier jet (SBJ) (Lundquist et al. 2010). Using seven years of hourly wind profiler data to characterize the SBJ, Lundquist et al. (2010) showed that in precipitation episodes occurring on days with SBJs, the orographic precipitation gradient is negatively correlated with SBJ height.

Shifts from snowfall to rainfall, and low summer streamflows, are two factors that tend to raise stream temperatures. Null et al. (2012, this special issue) develop a regional equilibrium temperature model to estimate stream temperatures for unregulated conditions. They present weekly simulated stream temperatures for Western Sierra streams subject to prescribed air temperature rises of 2˚, 4˚ and 6˚C. Their simulated stream temperatures on average rise 1.6˚C for every 2˚C rise in mean air temperature. Simulated warming is largest during spring, coinciding with the spring runoff recession. As with Stewart's hydrograph timing shifts, the sensitivity was greatest for those watersheds closer to the snow line. The highest-elevation watersheds of southern Sierra Nevada and the northern Feather River were least vulnerable.

Factors other than air temperature also influence stream temperature, and examining observational stream temperature records for the western U.S., Arismendi et al. (2012) found little association between air and stream temperature trends (see Figure 3 in that paper). They found both warming and cooling trends for locations with long records (starting 1950). For the most recent period (starting 1983), at sites with little human influence, about one-third of the sites had cooling trends in mean and minimum daily water temperature, roughly the same as those with warming trends in this period. They found that streams with greater riparian vegetation cover and higher baseflow indices were less likely to show warming trends and more likely to show cooling trends, although those factors have not been shown to fully account for the observed cooling. During spring and autumn, cooling trends were reported for at least 1 out of 4 of the streams studied. They emphasize the importance of long-term stream temperature records for proper evaluation and interpretation of trends, because these trends can vary and change from one multi-year period to another; and they emphasize the need for more widespread sensors to document spatial variability in trends.

Given the projected warming of stream water, Null et al. conclude that in future decades, coldwater habitat will be reduced overall and will be constrained to higher elevations in west-slope Sierra Nevada watersheds. Maintaining coldwater habitat for fish may require operating dams for thermal management, improving fish passage, or even dam removal. They also recommend that climatic changes be considered when planning stream restoration, preparing impact statements, or licensing operations of hydropower facilities. Of course, the human demand for artificial water storage will likely increase to partially compensate for the loss of snowpack storage.

Regardless of any protective effect of high elevations against temperature-driven hydrograph timing shifts (Stewart 2012, this special issue), several global climate models project timing shifts to earlier dates for precipitation itself. Costa-Cabral et al. (2012, this special issue, see Figures 1 and 2 in that paper) projected large hydrograph timing shifts to earlier dates in the high-elevation Mono-Owens watersheds. Projected shifts reach more than 1 month in one scenario by this century's end, namely, for global climate model CNRM under emission scenario A2, which projects about 4˚C warming combined with a 2-week shift to earlier precipitation timing. Very high elevation does however have a protective effect on the snowpack, and Costa-Cabral et al. also found that in the Mono-Owens watersheds April 1 SWE depends principally on precipitation totals rather than mean temperature.

Shifts in runoff timing will make it difficult to manage reservoirs for simultaneous flood control and conservation storage. Coats et al. (2012, this special issue) project an increase by up to 2.5-fold in the expected 100-yr flood magnitude on the Upper Truckee River, for the middle third of the 21st Century, for the GFDL-B1 climatology. The declining contribution of melting snow to summertime soil moisture storage will significantly increase drought severity, with implications for groundwater use, land use, and ecology. Impacts of these climate-driven changes on water supply in California and throughout the West have been observed or projected (see *online suppl. mat.* for literature references).

At Lake Tahoe, the direct effects of climate change on the lake will lead to increased thermal stability, reduced mixing and deepwater ventilation and, in the latter half of the century, deep-water anoxia, potentially resulting in the release of large quantities of available phosphorus and nitrogen from the enriched bottom sediments (Sahoo et al. 2012, this special issue). A large impact on algal growth may result if these nutrients are transported into the photic zone, with devastating consequences for the deep-water habitat of the resident salmonid community. Increased evaporation from the lake, especially if accompanied by a decline in precipitation – as projected by GFDL under emissions scenario A2 (Dettinger et al., Coats et al., Sahoo et al., all in this special issue) – may lead to lake level dropping below the rim for extended periods of time, depriving downstream users in the Truckee-Carson river basins with an important water source (Sahoo et al. 2012, this special issue). The temperature of incoming stream water, and its sediment content, also affects the insertion depth where it spreads and mixes (Sahoo et al. 2012, this special issue). These prospective changes make it all the more important to immediately reduce external nutrient sources to the Lake (Riverson et al. 2012, this special issue), and to plan for strong water conservation and water management programs in the Truckee-Carson river basins.

A striking result appears in Figure 5e of Costa-Cabral et al. (2012, this special issue) and corresponding equation (5), where a remarkably tight linear relationship is shown between 30-year averaged values of precipitation and simulated streamflow for the Mono-Owens watersheds above base-of-mountain stream gauges. This linear dependence of mean streamflow on mean precipitation, which exhibits the high value R^2=0.992, implying no dependence of sublimation-evapotranspiration (SET) losses on temperature, is seen also in the observational data (shown in the *Online Resource* of that paper).

The relationship represents a marked negative deviation from the evapotranspiration curve presented by Budyko (1974) as a function of potential evapotranspiration. Costa-Cabral et al. (2012, this special issue) explain the decoupling of mean annual SET from temperature on the basis of the seasonality of precipitation and snowmelt-runoff, and the soil's limited available water capacity. As temperature rises, snowmelt temperatures will be reached earlier in the year, but snowmelt still occurs at the same temperatures, near 0˚C. Later in the spring or summer, when temperature has risen well above 0˚C and potential evapotranspiration becomes high, evapotranspiration becomes water limited rather than energy limited. The results by Ficklin et al. (2012, this special issue) for Mono Lake, obtained separately and with a different hydrologic model, are in general agreement.

As noted by Budyko and Zubenov (1961; cited by Milly 1994), the deviations from the Budyko curve tend to be positive when precipitation and PET have seasonal variations that are in phase, and negative when they are out of phase. Milly (1994) pointed out the effect is present in Mediterranean climates (such as California's) especially when the soil water store is limited – as is certainly the case in the steep Eastern Sierra escarpments. Milly (1994) further identified the storminess of precipitation, i.e., the arrival of much of the precipitation volume in a few large storms (as is the case in the Sierra Nevada) as another cause. Further studies aimed at developing quantification of these effects are needed.

Water-limited conditions are also evident in the maps of simulated SET distribution for Lake Tahoe's watershed (Riverson et al. 2012, this special issue). In these Eastern Sierra regions, mean annual runoff will depend on uncertain future precipitation changes. Temperature will have an effect on seasonal runoff but hardly any on the annual water balance. Cold season runoff will increase due to the progressive transition from snow to rain, and the (projected) shifting of snowmelt to earlier dates. Warm season runoff will decline due to reduced snowpack store and earlier snowmelt, and will be limited by soil store capacity.

A limitation common to all projections in this special issue is the neglect of changes in vegetation that will result from future climatic change. Vegetation change will modify each watershed's hydrologic response to climate and the loads of sediment and nutrients into streams and lakes. The lowered soil moisture and runoff in the warm season appears as a possible limiting factor that may steer land cover changes in the future. Spontaneous or human-guided land cover adaptation to climate is difficult to predict and is beyond the scope of these studies, but progress in this regard is being made elsewhere (see Morelli et al. 2011), and its incorporation in hydrologic studies represents an important future research opportunity.

Given the importance of the altitudinal and temporal distribution of precipitation to specific watershed response, future studies will benefit from increased availability of regional climate model (RCM) simulations, with detailed representation of orographic precipitation. On the basis of high-resolution RCM simulations, Diffenbaugh et al. (2005) found a reduction of the precipitation-shadow effect, and a higher incidence of extreme high precipitation events, on the lee side of mountains throughout the western U.S. – a result due in part to the simulated higher moisture content of warmer air masses allowing significant moisture to be carried over the mountain crests and in part due to circulation changes.

The ongoing CalWater project (www.esrl.noaa.gov/psd/calwater) coordinated by NOAA (National Oceanic and Atmospheric Administration) seeks to test and improve climate model representation of *(i)* atmospheric rivers' amplitudes, frequencies and locations in climate models; and *(ii)* aerosols' role in cloud formation and precipitation (Ault et al., 2011). These are two key sources of uncertainty in California precipitation projections. Atmospheric rivers (so designated by Ralph et al. 2004) are the filamentary features created by the transport of large quantities of moisture from the southern Pacific Ocean by vigorous low-level jets, and are responsible for much of the Sierra's precipitation totals (Dettinger et al. 2004). Underwood et al. (2009) demonstrated that it has been storms generated by a specific type of midtropospheric circulation conditions which historically have produced high liquid precipitation totals on the Eastern Sierra, resulting in Truckee river flooding. Thus, the ability of climate models to accurately simulate future frequency of different types of storms is important.

Also absent from GCMs are microclimatic effects, such as Lake Tahoe's influence on its watershed's climatology, and the phenomenon of cold air pooling in mountain valleys (Daly et al. 2009; Lundquist et al. 2008). Lundquist et al. (2010), having characterized the importance of the Sierra barrier jet (SBJ) to orographic precipitation gradients in the Sierra, argue that a sufficiently fine-resolution climate model is needed that is able to represent SBJ characteristics, but admit the possibility that even this may be insufficient if it turns out that turbulence, which occurs at small spatial scales, plays a prominent role in orographic precipitation.

Finally, it is important to recognize that any watershed's response to climate change and climatic extremes will likely evolve over time, due to synergy among individual effects. The progressive decline in snow cover will eventually lead to reduced effects of rain on snow events, after an initial increase in those effects on peak streamflows. Because of reduced surface albedo, the watershed's response to both hot and cold events is expected to be amplified, and depleted soil moisture offers diminished latent cooling (Diffenbaugh et al. 2005). In summary, the expected rise in climatic extremes may be especially marked in the Eastern Sierra region as a result of fine-scale, localized climate dynamics, and we can expect the impacts of the extremes to be amplified or countered by synergetic effects among climate driven changes.

Acknowledgements

We thank Jessica Lundquist for her review, the literature references she indicated, and for helping identify some of the future research opportunities. We thank Michael Dettinger for downscaling the GCM output, and providing helpful advice on the Tahoe project. This manuscript also benefited from two anonymous reviews.

References

Arismendi I, Johnson SL, Dunham JB, Haggerty R, Hockman-Wert D (2012) The paradox of cooling streams in a warming world: Regional climate trends do not parallel variable local trends in stream temperature in the Pacific continental United States. *Geophys Resear Lett* 39(L10401). Doi:10.1029/2012GL051448

Ault AP, Williams CR, White AB, Neiman PJ, Creamean JM, Gaston CJ, Ralph FM, Prather KA (2011) Detection of Asian dust in California orographic precipitation. *J Geophys Res* 116(D16205). Doi:10.1029/2010JD015351

Budyko MI (1974) *Climate and Life*, Academic, San Diego CA, 508 pp

Budyko MI, Zubenov LI (1961) Determination of evaporation from the land surface (in Russian). *Izv Akad Nauk SSSR, Ser Geogr* 6:3-17

Cayan D, Tyree M, Dettinger M, Hidalgo H, Das T, Maurer E, Bromirski P, Graham N, Flick R (2009) Climate change scenarios and sea level rise estimates for the 2008 California climate change scenarios assessment. California Energy Commission, Sacramento, CA, p 62

Coats R (2010) Climate change in the Tahoe Basin: regional trends, impacts and drivers. Climatic Change 102:435-466

Coats RN, Perez-Losada J, Schladow G, Richards R, Goldman CR (2006) The Warming of Lake Tahoe. Climatic Change 76:121-148

Coats R, Costa-Cabral M, Riverson J, Reuter J, Sahoo G, Schladow G, Wolfe B (2012) Projected 21st century trends in hydroclimatology of the Tahoe basin. *Clim Change*, this Special Issue

Coats, RN, Larsen M, Heyvaert A, Thomas J, Luck M, Reuter J (2008) Nutrient and sediment production, watershed characteristics, and land use in the Tahoe Basin, California-Nevada. J *Am Water Resour Assoc* 44**:** 754–770

Costa-Cabral M, Roy SB, Maurer EP, Mills WB, Chen L (2012) Snowpack and runoff response to climate change in Owens Valley and Mono Lake watersheds. *Clim Change*, this Special Issue

Daly C, Conklin DR, Unsworth MH (2009) Local atmospheric decoupling in complex topography alters climate change impacts. *Int J Climatol*. doi:10.1002/joc.2007

Dettinger MD (2012) Projections and downscaling of 21st century temperatures, precipitation, radiative fluxes and winds for the southwestern US, with focus on Lake Tahoe. *Clim Change*, this Special Issue

Dettinger M, Redmond K and Cayan D (2004) Winter orographic precipitation ratios in the Sierra Nevada – Large-scale atmospheric circulations and hydrologic consequences. *J Hydrometeor* 5:1102-1116.

Diffenbaugh NS, Pal JS, Trapp RJ, Giorgi F (2005) Fine-scale processes regulate the response of extreme events to global climate change, *Proc Nat Acad Sci* 102(44):15774-15778

Ficklin DL, Stewart IT, Maurer EP (2012) Effects of projected climate change on the hydrology in the Mono Lake Basin, California. *Clim Change,* this Special Issue

Goldman CR (2000) Baldi Lecture: Four decades of change in two subalpine lakes. *Verh. Internat. Verein. Limnol.* 27:7-26

Hart J (1996) Storm over Mono: The Mono Lake Battle and the California Water Future. University of California Press, Berkeley CA

IPCC (2007) Climate Change 2007, the Fourth Assessment Report (AR4) of the United Nations ntergovernmental Panel on Climate Change (IPCC). The Physical Science Basis. Available at: http,//www.ipcc.ch/ipccreports/ar4-wg1.htm.

Jassby AD, Goldman CR, Reuter JE, Richards RC (1999) Origins and scale dependence of temporal variability in the transparency of Lake Tahoe, California-Nevada. Limnol. Oceanog 44:282-294

Kamerath M, Chandra S, Allen BC (2008) Distribution and impacts of warm water invasive fish in Lake Tahoe, USA. Aquatic Invasions 3 (1):35-41. doi:10.3391/ai.2008.1.1.7

Karl TR, Trenberth KE (2003) Modern global climate change. *Science* 302:1719-1723

Lahontan, NDEP (2010) Lake Tahoe Total Maximum Daily Load Final Report. California Regional Water Quality Control Board, Lahontan Region, Nevada Division of Environmental Protection, Carson City, Nevada

Lundquist JD, Minder J, Neiman PJ, Sukovich E (2010) Relationships between barrier jet heights, orographic precipitation gradients, and streamflow in the northern Sierra Nevada. *J Hydrometeor* 11:1141-1156

Lundquist JD, Pepin N, Rochford C (2008) Automated algorithm for mapping regions of cold-air pooling in complex terrain. *J Geophys Res* 113(D22107). Doi:10.1029/2008JD009879

Lundquist JD, Cayan DR (2007) Surface temperature patterns in complex terrain: Daily variations and long-term change in the central Sierra Nevada, California. *J Geophys Res* 112(D11124). Doi:10.1029/2008WR007035.

Manning MR, Edmonds J, Emori S, Grubler A, Hibbard K, Joos F, Kainuma M, Keeling RF, Kram T, Manning AC, Meinshausen M, Moss R, Nakicenovic N, Riahi K, Rose SK, Smith S, Swart R, van Vuure DP (2010) Misrepresentation of the IPCC CO2 emission scenarios. Letters, Nature Geosci 3

Maurer EP, Brekke L, Pruitt T, Duffy PB (2007) Fine-resolution climate change projections enhance regional climate change impact studies. Eos, Transactions of the American Geophysical Union 88(47):504. doi:510.1029/2007EO470006

Milly PCD (1994) Climate, soil water storage, and the average annual water balance. *Water Resour Res* 30(7):2143-2156

Morelli TL, McGlinchy MC, Neilson RP (2011) A climate change primer for land managers: an example from the Sierra Nevada. *Research Paper PSW-RP-262.* Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 44 p

Nakicenovic N, et al. (2000) Special report on emissions scenarios. Cambridge U. Press, Cambridge UK, 570 pp

Null SE, Viers JH, Deas ML, Tanaka SK, Mount JF (2012) Stream temperature sensitivity to climate warming in California's Sierra Nevada: impacts to coldwater habitat. *Clim Change*, this Special Issue

Ralph FM, Neiman PJ, Wick GA (2004) Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North Pacific Ocean during the winter of 1997/98. *Mon. Wea. Rev.* 132:1722-1745

Raupach MR, Marland G, Ciais P, LeQuere C, Canadell JG, Field CB (2007) Global and regional drivers of accelerating CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America (PNAS).* Doi:10.1073/pnas.0700609104.

Riverson J, Coats R, Costa-Cabral M, Dettinger M, Reuter J, Sahoo G, Schladow G, Wolfe B (2012) Modeling the impacts of climate change on streamflow, nutrient and sediment loads in the Tahoe Basin. *Clim Change*, this Special Issue

Sahoo GB, Schladow SG (2008) Impacts of climate change on lakes and reservoirs dynamics and restoration policies. Sustainability Sci 3 (2):189-200

Sahoo GB, Schladow SG, Reuter JE (2010a) Effect of Sediment and Nutrient Loading on Lake Tahoe (CA-NV) Optical conditions and restoration opportunities using a newly developed lake clarity model. Water Resour Res doi:10.1029/2009WR008447

Sahoo GB, Schladow SG, Reuter JE, Coats R (2010b) Effects of climate change on thermal properties of lakes and reservoirs, and possible implications. Stochastic Environmental Research and Risk Assessment (SERRA), DOI 10.1007/s00477-010-0414-z

Sahoo G, Schladow G, Reuter JE, Coats R, Dettinger M, Riverson J, Wolfe B, Costa-Cabral M (2012) The response of Lake Tahoe to climate change. *Clim Change*, this Special Issue

Serreze MC, Clark MP, Armstrong RL, McGinnis DA, Pulwarty RS (1999) Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data. *Water Resour Res* 35:2145-2160

SNEP (SNEP Science Team and Special Consultants, University of California) (1996) The Sierra Nevada Ecosystem Project: Final Report to Congress. http://ceres.ca.gov/snep/

Stewart IT (2012) Connecting physical watershed characteristics to climate sensitivity for California mountain streams. *Clim Change*, this Special Issue

Swift TJ, Perez-Losada J, Schladow SG, Reuter JE, Jassby AD, Goldman. CR (2006) Water clarity modeling in Lake Tahoe: Linking suspended matter characteristics to Secchi depth. Aquatic Sciences 68:1-15

TERC (2011) Lake Tahoe Clarity. At: http://terc.ucdavis.edu/research/clarity.html Accessed 8/30/2011

Tetra Tech (2010) *Upland Sources* – Lake Tahoe Total Maximum Load Technical Report (Section 4-3). In *Lake Tahoe Total maximum Daily Load Final Report.* California Regional Water Quality Control Board, Lahontan Region, Nevada Division of Environmental Protection, Carson City NV: 4-23 to 4-99 pp

Underwood SJ, Kaplan ML, King KC (2009) The role of upstream midtropospheric circulations in the Sierra Nevada enabling leeside (spillover) precipitation. Part I: A synoptic-scale analysis of spillover precipitation and flooding in a leeside basin. *J Hydrometeor* 10:1309-1326. Doi:10.1175/2009JHM1105.1

Wittmann M, Reuter J, Schladow SG, Hackley SH, Allen BC (2008) Asian clam (*Corbicula fluminea*) of Lake Tahoe: Preliminary scientific findings in support of a management plan. U. California Tahoe Environmental Research Center, Davis CA

Wolfe B (2010) Implications of climate change for design of BMPs in the Lake Tahoe basin. In: Coats R and Reuter J (ed) *The Effects of Climate Change on Lake Tahoe in the 21st Century. Meteorology, Hydrology, Loading and Lake Response.* University of California, Davis, Tahoe Environmental Research Center and Department of Environmental Science & Policy, Davis CA, pp 68-80

Wood AW, Maurer EP, Kumar A, Lettenmaier DP (2002) Long-range experimental hydrologic forecasting for the eastern United States. *J Geophys Res* 107(D20): 4429. doi:4410.1029/2001JD000659