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Projected 21st century trends in hydroclimatology of the Tahoe basin

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Abstract With down-scaled output from two General Circulation Models (the Geophysical Fluid Dynamics Laboratory, or GFDL, and the Parallel Climate Model, or PCM) and two emissions scenarios (A2 and B1), we project future trends in temperature and precipitation for the Tahoe basin. With the GFDL, we also project drought conditions and (through the use of a distributed hydrologic model) flood frequency. The steepest trend (GFDL with A2)

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indicates a 4–5°C warming by the end of the 21st century. Trends in annual precipitation are more modest with a dip in the latter half of the 21st century indicated by the GFDL/A2 case, but not the others. Comparisons with the Palmer Drought Severity Index show that drought will increase, in part due to the declining role of the snowpack as a reservoir for soil moisture replenishment. Analysis of flood frequency for the largest watershed in the basin indicates that the magnitude of the 100-yr flood could increase up to 2.5-fold for the middle third of the century, but decline thereafter as the climate warms and dries. These trends have major implications for the management of land and water resources in the Tahoe basin, as well as for design and maintenance of infrastructure.

1 Introduction

Understanding of the historic and likely future conditions of Lake Tahoe's water quality and famed optical transparency requires consideration of the input of water, nutrients, sediment and energy from the lake's watershed and from the atmosphere (e.g., Jassby et al. 2003; Reuter et al. 2003; Sahoo et al. 2010). Previous work on the historic trends in the basin's hydroclimatology (1910–2007) indicated strong upward trends in air temperature (especially night-time temperature), a shift from snowfall to rain, a shift in snowmelt timing to earlier dates, increased rainfall intensity, increased interannual variability, and an increase in the temperature of Lake Tahoe (Coats et al. 2006; Coats 2010). A comparison of the rates of change in the Tahoe basin with those of the surrounding region (weather and stream gaging stations within 22 km of the basin) indicates that the former is warming faster than the latter.

With continued change toward a warmer climate (IPCC, 2008; Hansen et al. 2009), both research scientists and resource managers in the Tahoe basin would like to know: 1) how fast is the air temperature in the basin likely to rise, 2) how are the form, timing and annual amount of precipitation likely to change, 3) how will the changes in temperature and precipitation affect drought conditions, and 4) how will changes in precipitation affect streamflow regimes, especially high- and low-flow frequency-magnitude relationships? The purpose of this paper is to begin answering these questions based on projected future conditions, and thus provide a link for understanding the chronology of recent and expected changes brought about by climate change. Our approach was to downscale the output for the 21st century from two General Circulation Models (GCMs) and two emissions scenarios, and use the downscaled output to drive a distributed basin hydrology model. The output from the hydrology model provides streamflow and soil moisture projections, from which projected flood frequency, flow duration, drought severity and shifts in snowmelt timing are calculated, for selected sub-basins and sites in the Tahoe basin. For a more detailed description of the Tahoe basin and regional climate, see Costa-Cabral et al. (2012, this issue).

2 Methods

2.1 Projecting future climate with global climate models

Two General Circulation Models (also known as Global Climate Models, or GCMs) were selected for this study: the Geophysical Fluid Dynamics Laboratory, or GFDL CM2.1 (Delworth et al. 2006) and the Parallel Climate Model, or PCM1 of the National Center for Atmospheric Research (Washington et al. 2000)). These models were selected because they vary in their responsiveness to increasing greenhouse gas emissions, with the GFDL being more responsive, and the PCM less so (Dettinger 2012, this issue).

For each GCM, two contrasting scenarios of future greenhouse gas emissions were selected: the A2 and B1 (Nakicenovic et al. 2000), which respectively lead to 830 and 550 ppmv of CO_2 by year 2100. The A2 scenario represents a world with uneven economic growth and large income gaps between now-industrialized and developing world regions, where people, ideas and capital have limited mobility, and where technology diffuses more slowly (Cayan et al. 2009). Although the A2 is the highest emission scenario for which most modeling groups have completed simulations, the 21st century emissions to date already surpass those of the 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).

Global climate models simulate large-scale (200–500 km) circulation patterns, temperature and precipitation (the latter with lesser accuracy). Before GCM results can be useful for localized hydrologic applications, however, two computational techniques must be applied. First, there is a scalar mismatch between the needs of a hydrologic model (typically applied at a spatial scale within 0.01°–0.5°) and the coarse scale of GCMs (2°–5°). “Downscaling” refers to the process of generating finer spatially-resolved data from the coarse GCM data. For our application in the Tahoe basin, the daily GCM results were downscaled to a 7.5 min (1/8°; about 12 km) grid scale, using the method of constructed analogues (Hidalgo et al. 2008; Dettinger 2012, this issue). In this procedure, a set of days is identified (for each season) having the same coarse-scaled climate pattern as the modeled historical record. Then the linear combination of weather maps that best fit the model pattern is determined by linear regression, and the regression equations are applied to high resolution maps of the explanatory variables. The downscaling procedure also incorporated a high-resolution regional climate reanalysis (called CARD10) of the meteorology over California and Nevada (Dettinger, 2012 this issue).

2.2 Bias correction of precipitation data

The second computational step before the GCM results can be used to assess regional hydrologic impacts is called bias correction. The precipitation dataset resulting from constructed analogues downscaling, when compared to historical (1950–1999) observations at the meteorological stations near Lake Tahoe, showed an excess of precipitation days over the historical period, resulting in under-estimated mean daily precipitation intensity. The issue was not an over-abundance of low-precipitation days (the “model drizzle” that is common in daily GCM results; see e.g. Piani et al. 2010) but too many event days for all daily-precipitation magnitude classes. While the shape of the downscaled simulated distribution of precipitation intensities was similar to point observations, the number of rain days was higher than observations. On the other hand, the mean daily intensity of precipitation on wet days was lower than observations. To correct this, the simulated precipitation time series for the historical period produced by both of the GCMs were modified using random event selection to reduce the number of wet days. In this procedure, each event regardless of length had equal likelihood of being removed from the data set of simulated precipitation. See Online Resource 1 for details.

The GCM-simulated precipitation time series for the historical period was then subjected to “quantile mapping,” similar to the BCSD (bias correction and statistical downscaling) technique introduced in Wood et al. (2002, 2004). An important difference between our quantile mapping procedure and that introduced in Wood et al. is that we used a daily time scale rather than monthly. In our quantile mapping, for any one of the 12 months, each simulated daily precipitation value *x* is replaced by the observed value *x'* having the same plotting position as *x*.

The distribution of annual maxima is well represented in the downscaled time series for the annual 1-day maxima, but the highest values of 3-day annual maxima (for both GFDL and PCM) are under-represented. This is tentatively attributed to a lower degree of temporal correlation in the simulated time series during heavy storms, as compared to observations**.** Because intense, long-duration storms, and 3-day storms in particular, are capable of generating high runoff rates and play an important role in sediment and pollutant transport, the lowered frequency of 3-day annual maxima may lead to under-estimation of peak runoff and transport rates and contributes to uncertainty of results.

For the four model/scenario combinations, both total annual and total monthly precipitation (averaged over the Tahoe basin) were calculated, and trends tested with Mann-Kendall test (Helsel et al. 2005; Helsel and Frans 2006).

The downscaling and bias correction procedures still cannot produce the spatial variability in temperature and precipitation in the mountainous terrain of the Tahoe basin. In order to create input files for a distributed hydrology model, we used temperature and precipitation from a network of 12 SNOTEL stations (NRCS 2010). Because elevation varies by subwatershed, local lapse rates were used to adjust temperature to reflect topographic influence (i.e. subwatersheds with higher elevation than the assigned gages will be colder than subwatersheds with lower elevation). This in turn has a direct impact on whether precipitation arrives as rain or snow, and in turn, the quantity of precipitation during snowfall events. Daily values of temperature were disaggregated to hourly values using observed statistical distributions of hourly values in the SNOTEL data. Temperature was disaggregated to hourly values using observed diurnal distributions (by month) at the South Lake Tahoe airport (see Riverson et al. 2012, this issue). These procedures incorporate the effects of local topography in the hydrologic model.

2.3 Hydrologic modeling

The hydrologic impacts of climate change were simulated using a distributed hydrologic model, the Load Similation Program C++ (LSPC). This model, which evolved from the Stanford Watershed Model (Crawford and Linsley 1966), was selected for development of the Lake Tahoe Watershed Model. LSPC is a U.S. Environmental Protection Agency-approved modeling system that includes Hydrologic Simulation Program–FORTRAN (HSPF) algorithms for simulating watershed hydrology, erosion, and water quality processes. It also simulates snowmelt and in-stream transport processes, and routes flow downstream in a channel network, producing hourly discharge and concentrations of water quality constituents. A detailed discussion of simulated processes and model parameters is available as part of the HSPF User's Manual (Bicknell and Imhoff 1997), and its application in the Tahoe basin is described by Riverson et al. (2012, this issue).

The downscaled daily maximum and minimum air temperatures were used to calculate daily and annual averages for individual grid points, as well as basin-wide averages for the 12 grid cells. The results were plotted to illustrate the future temperature trends, and the average daily temperature was used with the adjusted precipitation data to examine the trend in fraction of precipitation falling as snow over the entire basin.

Trends in Tahoe basin wind enter into our modeling in two ways. First, wind plays a minor role in the snowmelt routine of the LSPC, since warm winds accelerate snowmelt. During a rain-on-snow event, the transfer of sensible heat from the air by advection contributes more to melting the pack than the heat content of the rain. Second, wind plays a major role in mixing the lake (see Sahoo et al. 2012 this issue). For a discussion of the bias correction for wind speed, see On Line Resource 1, and for the modeling of wind, see On Line Resource 2.

2.4 Drought severity

The Palmer Drought Severity Index (PDSI) is a widely-used and convenient index of regional drought, that can characterize the effect of climate change on drought duration and severity (Kothavala 1999). Palmer (1965) defined a drought period as “an interval of time…during which the actual moisture supply at a given place rather consistently falls short of the climatically expected…moisture supply.” The index is based on a soil water balance model in which the soil is treated as two connected “buckets”. Evapotranspiration is calculated by the empirical Thornthwaite (1948) method. PDSI can be calculated at a weekly or monthly time scale from average weekly or monthly temperature, precipitation and available water capacity (AWC) of the soil. Soil water deficit in the model is cumulative, so that the index reflects the persistence of a drought. The simplicity and relatively low data requirements are both an advantage and weakness of the PDSI (Alley 1984).

The PDSI calculation involves calculating a set of four water balance coefficients from regional climate data, for potential evapotranspiration, potential recharge, potential loss and potential runoff. The formulation of the model that we used is “self-calibrating” in that these four coefficients are calculated for each set of input precipitation and temperature data, in order to produce a predetermined distribution of the PDSI (Wells et al. 2004). This means that the PDSI values for one climatic region or time period cannot be compared with those of another, because both results will have about the same distribution of PDSI values. The method can be used to compare time trends between regions or between climate change scenarios, although Dai (2010) cautions that since all drought indices have been defined and calibrated for the current climate, future PDSI values may be greatly out of the range for which it was developed.

In order to calculate the PDSI, we selected two subwatersheds in the Tahoe Basin, one near Tahoe City, with relatively high precipitation, and one near Glenbrook, in the driest part of the basin. We used the LSPC hydrology model (Riverson et al. 2012, this issue) to generate daily rainfall, snowmelt and runoff, along with average daily air temperature for each site. Daily snowmelt was added to rainfall to generate total soil water input, so the PDSI model results should reflect the impact of changes in snowfall and snowmelt timing on available soil water. Modeled daily values of soil water input were added and temperature values were averaged to get weekly input data for use in the PDSI model. Available water capacity values were taken from the NRCS Soil Survey Report for the Tahoe basin (Rogers et al. 1974).

2.5 Streamflow regimes

The projected shift in snowmelt timing over the 21st century was characterized using the variable Center Timing (CT), which gives the date of the centroid of the annual hydrograph (Barnett et al. 2008; Stewart et al. 2005). The centroid date is defined as the discharge-weighted mean day in the water year, that is: $CT=\Sigma(t_i q_i)/\ \Sigma(q_i)$, where t_i=the ith day in the water year, and q_i=mean daily discharge on the ith day.

Previous work on the shift in snowmelt timing in the Tahoe basin examined the trends in both the spring snowmelt peak timing (SMPT) and CT (Coats 2010). The former (based on the residual after removing the effect of total annual snowfall) is more sensitive to spring temperature trends, and for five streams in the Tahoe basin, the timing shift (1972–2007) averaged −4 days per decade, whereas the CT did not show significant trends for basin streams. The CT is thus a more conservative measure of the shift in runoff timing than the SMPT, possibly because springtime air temperatures in the Sierra are increasing faster than those in fall and winter (Coats 2010; Cayan et al. 2009). The CT has the advantage that it is influenced by large winter rainstorms as well as by snowmelt, whereas the SMPT only reflects snowmelt timing.

The LSPC hydrology model was used to calculate the hourly streamflow based on the GFDL B1 and A2 scenarios for each of the 63 individual watersheds as they drain into Lake Tahoe (modeled as 183 subwatersheds) (Riverson 2010). In examining the effects of climate change on streamflow, we focused on the Upper Truckee River (UTR), the largest tributary of Lake Tahoe (basin area of 142 km^2), accounting for about 17% of the annual runoff to the Lake (Jeton 1999). The highest elevation in the UTR basin is 3,067 m, and at the higher elevations in the basin, much of the annual precipitation falls as snow. From the UTR hourly discharge we calculated the mean daily discharge (MDQ) and the CT date for each year.

For the MDQ values from the GFDL B1 and A2 scenarios, we developed flow duration curves for the UTR, for the early-century (2001–2033), mid-century (2034–2066) and late-century (2067–2099) time periods. A flow duration curve shows the percent of the time that a given discharge is equaled or exceeded. To remove bias in the LSPC/GFDL flow duration curves for daily discharge, we calculated flow duration curves from both the U.S. Geological Survey record (USGS 2009) for measured discharge (Sta. No. 10336610), and from the GFDL/LSPC modeled output for the same historic period (1972–1999). See Online Resource 1 for details of the correction procedure.

A flow-duration curve is useful for characterizing the total time distribution of stream discharge, but it is not very useful for showing the frequency of extreme high and low discharge events. To analyze the projected changes in flood frequency of the UTR over the 21st century, we first compared the flood frequency curve from the historic (1972–1999) gage record for the UTR with the curve derived from the maximum annual LSPC/GFDL hourly discharge for the same period. Log-Pearson flood frequencies were estimated with the method of Bulletin 17B (USGS 1981), except that outliers were not excluded .

The comparison of the two flood frequency curves for the historic period showed that the LSPC/GFDL curve was somewhat higher than the curve from the gage data (See Online Resource 1, Fig. 6). To adjust the modeled output to the same scale as the measured discharge, we used a linear regression of the log flood magnitude from the USGS data vs. the modeled log flood magnitude for the same historic period, at equal recurrence intervals ($R^2=0.997$). See Online Resource 1 for details of the adjustment. The adjusted flood frequency for three 33-yr periods in the 21st century were then compared with the calculated historic curves for the UTR. Significance of the apparent differences was tested with the method of Zou and Donner 2008.

The previously observed shift in snowmelt timing (Coats 2010) suggests that we might expect an increase in frequency of low-flow events. To test this hypothesis, we calculated the annual minimum 5-day low flow for the UTR for the GFDL A2 and B1 cases, and tested for a time trend over the 21st century, using Mann-Kendall test (Helsel and Frans 2006; Salmi et al. 2002).

3 Results and discussion

3.1 Air temperature

Figures 1a-d show the projected average annual T_{max} and T_{min}, averaged over the entire Tahoe basin, for the A2 and B1 emissions scenarios, according to the PCM and GFDL

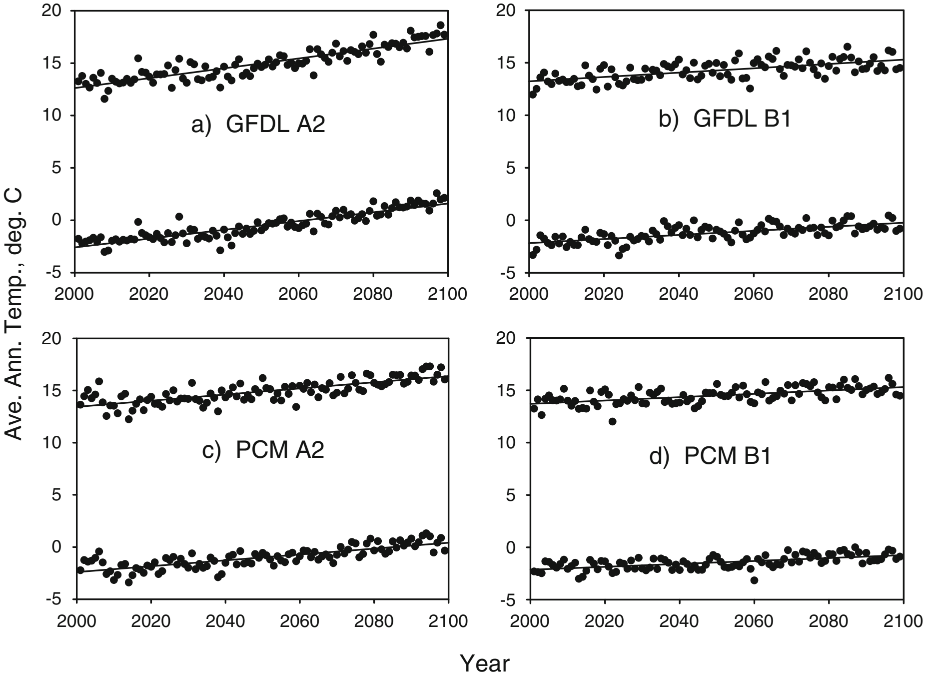


Fig. 1 **a-d** Projected average annual Tmax and Tmin, averaged over the Tahoe basin, for the A2 and B1 emissions scenarios, from the GFDL and PCM results

models. The upward trends for the A2 scenario are greater than for the B1, and the GFDL model tends to produce a more rapid warming trend than the PCM. The trend for the GFDL A2 amounts to an increase over the 21st century of about 5°C. At an average adiabatic lapse rate, this is equivalent to moving the lake from its present elevation of 1900 m down to an elevation of about 1130 m.

3.2 Precipitation

The modeled 21st century trends in total annual precipitation are shown in Fig. 2a-d. These totals represent bias-corrected basin-wide averages, as explained above. The curves are from a LOWESS smoothing (Helsel and Hirsch 1995). The trends are not very striking, except perhaps for the drying trend for the GFDL A2 case during the latter half of the century. It is important, however, to examine the trends in timing as well as total annual precipitation. Figure 3 shows the monthly and annual trend including the Sen's slopes from the Mann-Kendall test for the four model/scenario combinations. Though the trends are small, they are highly significant, especially for the GFDL results.

The trends in the form of precipitation may be more important than trends in total annual amount. The shift from snow to rain (annual totals averaged over the entire basin) is shown in Fig. 4, and Table 1 shows the Sen's slopes and significance level of trends in the percent of annual precipitation falling as snow. Since the average includes the area over the lake itself, the trend slope is greater than the trend averaged for the 183 subwatersheds (Riverson 2010; Riverson et al. 2012, issue), but comparable to the historic shift at Tahoe City, shown in Coats (2010). The shift from snow to rain will result in less springtime water storage in the

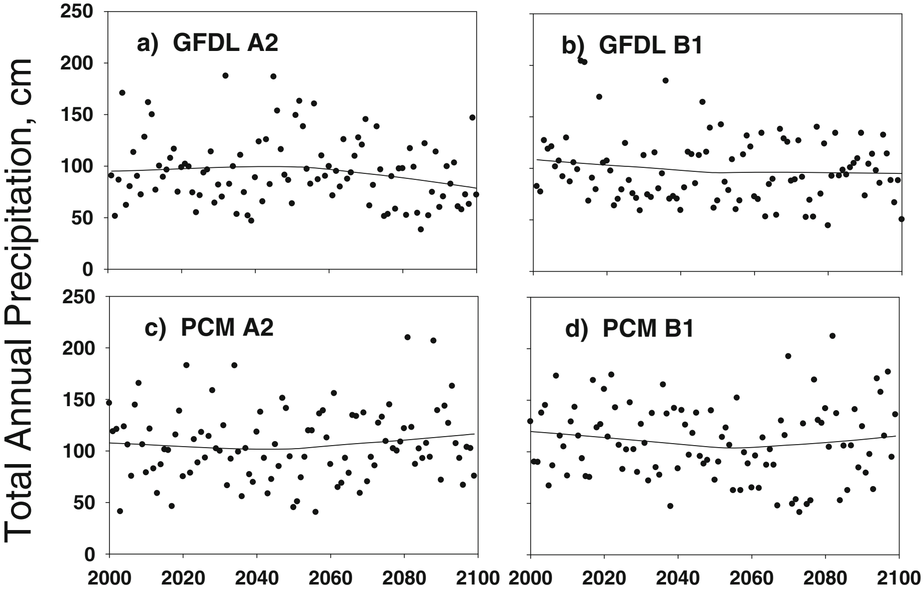


Fig. 2 **a-d** Bias-corrected annual precipitation, averaged over the Tahoe basin, for the A2 and B1 emissions scenarios, from the GFDL and PCM results

pack. This will decrease the water availability for plants, and contribute to earlier drying of fuels on the forest floor (Westerling et al. 2006).

The modeled trends from snow to rain in Fig. 4 may slope less steeply downward than the actual slopes. In a study based on 30 years of snow survey data (1966–1996) from 260 snow courses in the Sierra Nevada, Johnson et al. (1999) found that the Tahoe basin had the highest loss—54%—in May snow water equivalent (SWE) of any of the 21 river basins studied. This is consistent with the observation of Coats (2010) that the historic warming trend for the Tahoe basin is higher than that of the surrounding region.

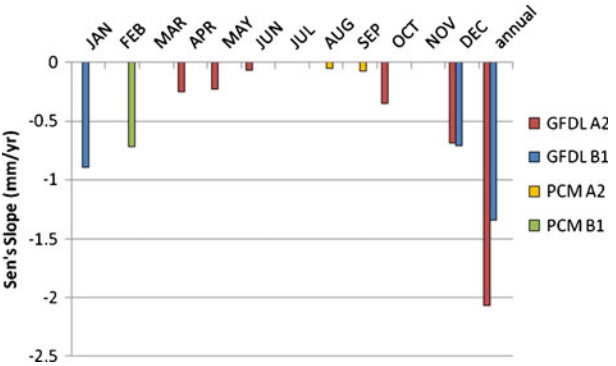


Fig. 3 Trends in monthly and annual precipitation having statistical significance higher than 0.90 in all cases, as determined by the Mann-Kendall test for trends. For GFDL, all monthly trends shown have significance higher than 0.99

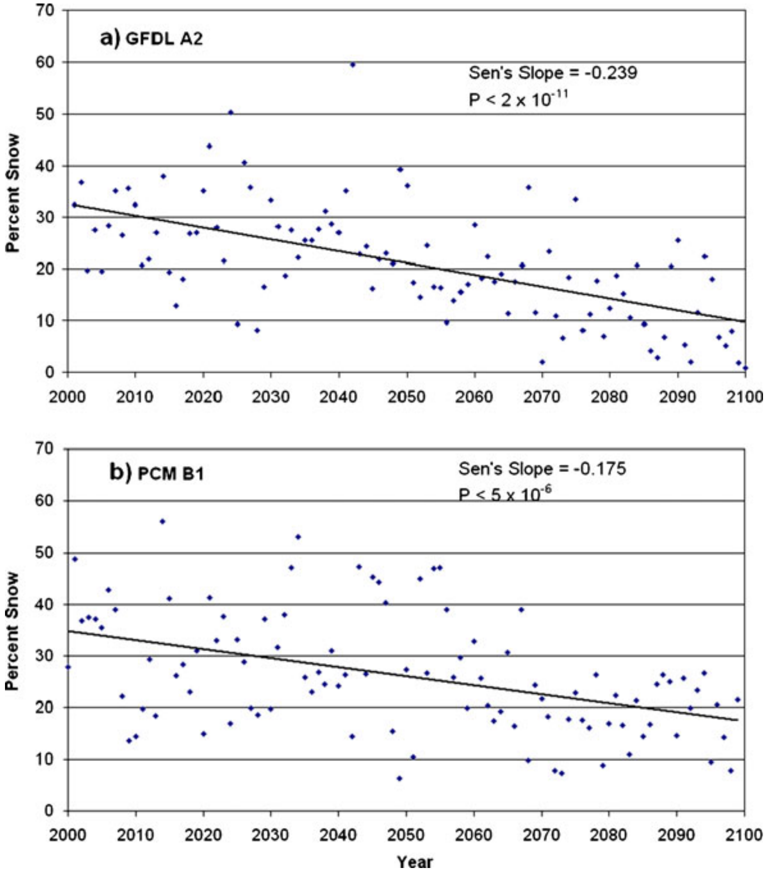


Fig. 4 The trend in the percentage of total annual precipitation falling as snow in the 21st century, averaged over the Tahoe basin

3.3 Drought and summer low-flow

The Palmer Drought Severity Index (PDSI) responded to the modeled changes in temperature and precipitation over the 21st century, and the results for the east and west sides of the lake were somewhat different. Figure 5 shows minimum annual PDSI for Tahoe City (west shore, high precipitation), and Glenbrook (east shore, low precipitation) for the GFDL A2 and B1 scenarios. Note that a low (especially negative) PDSI value indicates more arid conditions. For the A2 scenario at both Tahoe City and Glenbrook, there is no significant trend to mid-century, but a decline in water availability during the 2nd half of the century is

Table 1 Estimated Sen's slope and significance level (from the Mann-Kendall test, one-tailed) for trends in the percent of total annual precipitation falling as snow, averaged over the Tahoe basin

Case	Sen's slope estimate	P<
PCM B1	−0.175	4.4E-06
PCM A2	−0.194	6.3E-07
GFDL B1	−0.195	1.1E-07
GFDL A2	−0.239	2.1E-11

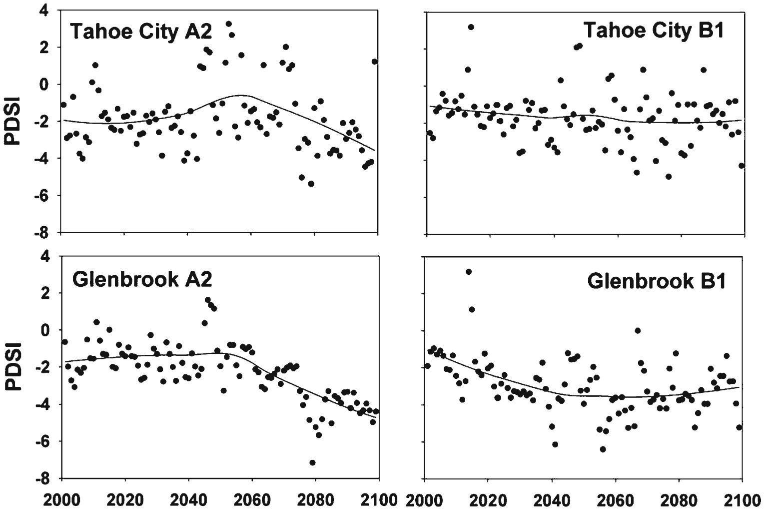


Fig. 5 Trends in the minimum annual weekly Palmer Drought Severity Index, at Tahoe City and Glenbrook, for the GFDL A2 and B1 Scenarios

indicated. With the B1 scenario there is a slight decline to mid-century at Tahoe City and no trend in the latter half of the century, but at Glenbrook, there is a relatively steep decline to mid-century, with leveling off thereafter. Table 2 shows the significance of time trends in annual minimum PDSI for the four cases, by half-century periods.

The increasing aridity in latter half of the 21st century for the A2 scenario, especially on the dry east side of the basin, is related to the reduced role of snowmelt in the soil water balance, as well as declining precipitation and increasing evapotranspiration. Figure 6 shows the time trends in the percent contribution of snowmelt to soil water input, and Table 3 shows the OLS regression results for annual minimum weekly PDSI vs. percent of total annual infiltration as snowmelt. As precipitation shifts from snow to rain, less snowmelt water is available in late spring and early summer to maintain available soil moisture, and summer drought becomes more severe. On the east side of the basin the snowpack is typically thinner than on the west side, so the shift from snow to rain has a relatively greater impact on the east side.

With both the B1 and A2 scenarios, the GFDL shows a downward trend in the Center Timing of annual runoff of the UTR (Figs. 7a and b) over the 21st century. The shift toward earlier dates

Table 2 Estimated Sen's slope and significance level (from the Mann-Kendall test) for trends in the minimum annual weekly Palmer Drought Severity Index (PDSI), at Tahoe City and Glenbrook, for two emissions scenarios

	2001–2050		2050–2099	
	Sen's slope estimate	P<	Sen's slope estimate	P<
Tahoe City B1	−0.014	0.102	0.004	NS
Tahoe City A2	0.009	NS	−0.061	9.53E-05
Glenbrook B1	−0.046	5.96E-05	0.020	NS
Glenbrook A2	0.006	NS	−0.069	3.54E-09

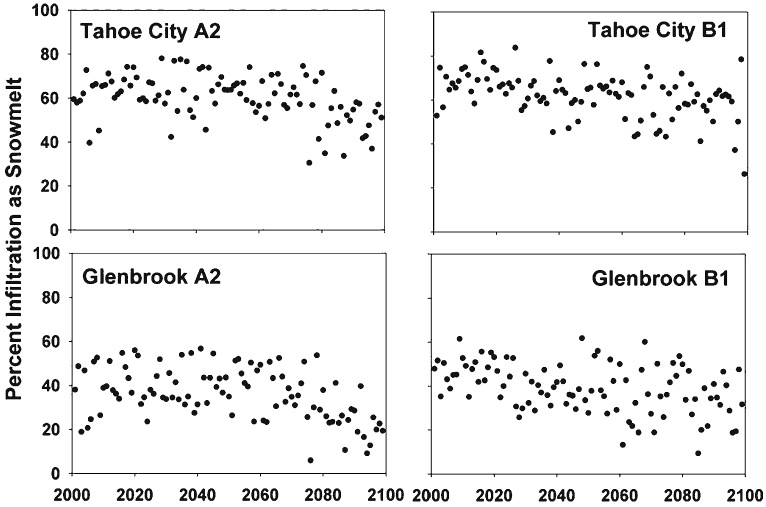


Fig. 6 Trends in the percent of total annual infiltration as snowmelt at Tahoe City and Glenbrook, for the GFDL A2 and B1 Scenarios

in the hydrograph centroid reflects both earlier spring snowmelt and the shift in precipitation from snow to rain. The trend in CT is consistent with the results of Dettinger et al. 2004; Cayan et al., 2009; Dettinger and Cayan 1995; Johnson et al. 1999; and Stewart et al. 2005.

The shift in CT is reflected in the flow duration and low-flow statistics, at least for the A2 scenario. Figure 5 in Online Resource 1 shows the flow duration curves for the UTR from both the USGS gage record (1972–1999) and the modeled runoff from the GFDL and LSPC for the same period. These are the curves used in the quantile mapping to adjust the B1 and A2 flow duration curves for the three 33-yr periods shown in Figs. 8(a) and (b). In the B1 scenario, the curve for the 2034–66 period falls below the other 3 curves, but the difference is slight. For the A2 scenario, the daily streamflow for last third of the century falls well below the curves for the early-century and mid-century, and below the historic gage data curve. The shifts in the flow duration curves are reflected in the annual yields for the UTR. The downward trend in annual streamflow (Sen'slope) over the 21st century is -0.28×10^6 m^3yr^{-1} ($P<0.03$) for the A2 scenario, and -0.22×10^6 m^3yr^{-1} for the B1 scenario ($P<0.08$).

From a resource management perspective, the changes in low-flow may be more important than the flow duration statistics. Figure 9 shows the time trend (Sen's slope) in the annual minimum 5-day low flow for the UTR for the A2 scenario (-0.75 liters sec^{-1} yr^{-1}; $P<0.0007$). There is no trend in the 5-day low flow under the B1 scenario.

The UTR (like many of the Basin streams) flows through coarse alluvium in its downstream reaches, and in very dry years, there is no virtually no surface flow. The unadjusted

Table 3 OLS regression results for minimum weekly PDSI vs. percent infiltration as snowmelt, at Tahoe City and Glenbrook, for two emissions scenarios

	R^2	P<
Tahoe City B1	0.15	5.80E-05
Tahoe City A2	0.19	5.70E-06
Glenbrook B1	0.19	6.10E-06
Glenbrook A2	0.26	5.80E-08

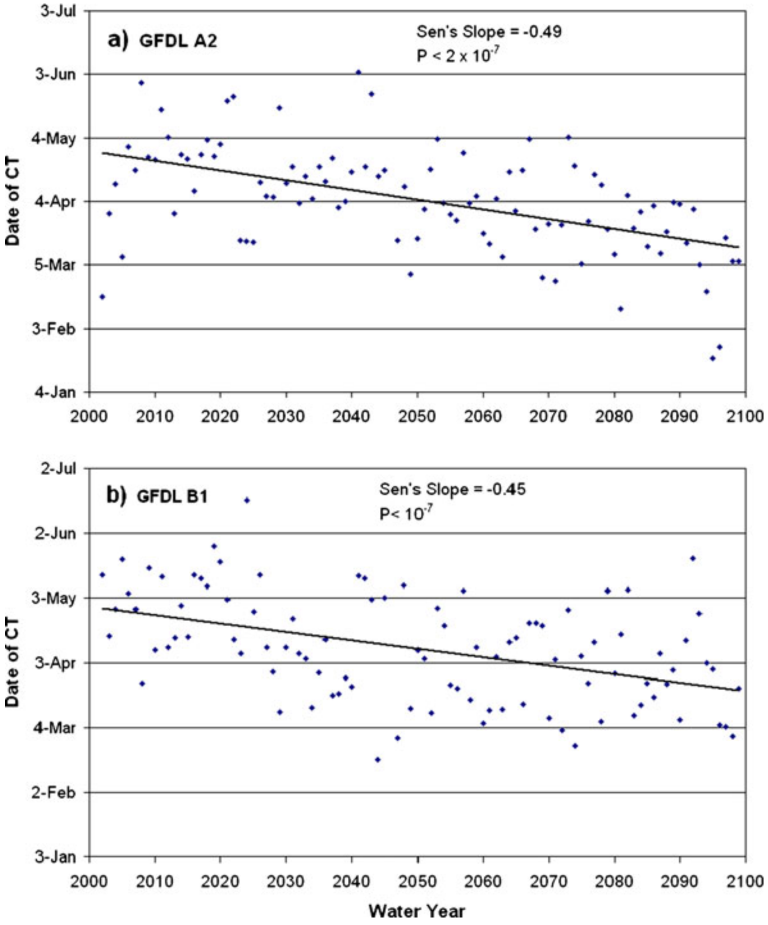
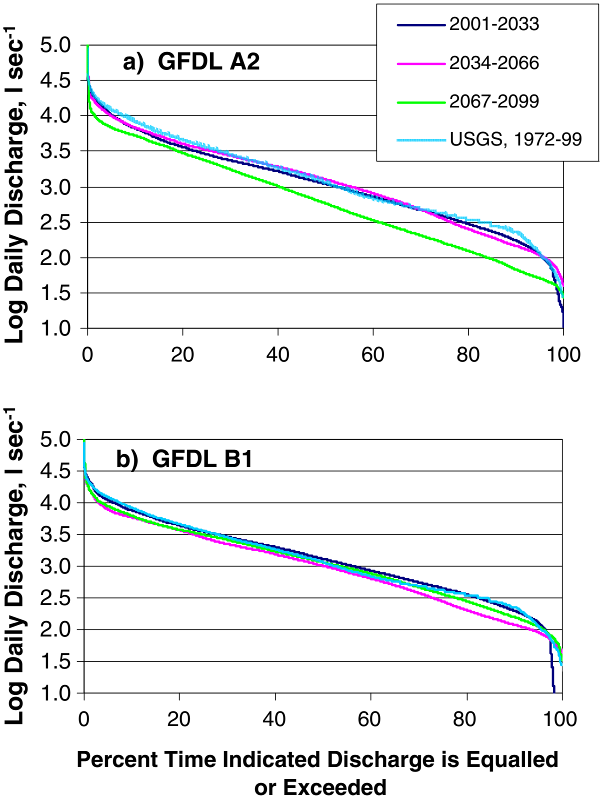


Fig. 7 **a**-**b** Trends in the Center Timing of annual runoff for the Upper Truckee River (UTR), from the GFDL B1 and A2 Scenarios

modeled output from the LSPC does not take account of the infiltration loss of streamflow in these reaches (Fig. 5 in Online Resource 1), but the adjusted flow-duration curves do. With the A2 scenario, the frequency of complete drying in the lower reaches of Tahoe basin streams will increase, especially in the latter half of this century.

Using WEAP21, a weekly one-dimensional rainfall-runoff model, Null et al. (2010) modeled the effects of uniform increases in air temperature of 2°, 4° and 6°C (with historical hydrology) on mean annual flow (MAF), centroid timing (CT) and low-flow duration (LFD), for 15 river basins on the west slope of the Sierra Nevada. They found that the sensitivity of the these variables to warming varied considerably with elevation, soils, vegetation and watershed area, with watersheds in the northern Sierra Nevada being the most vulnerable to reductions in MAF. Watersheds at intermediate elevations throughout the Sierra were most sensitive to timing shifts in CT, and those in the central Sierra Nevada were the most affected by increased LFD. For the UTR, we see effects on all three streamflow metrics.

Fig. 8 **a-b** Adjusted flow duration curves for the UTR for the periods 2001–2033, 2034–2066 and 2067–2099, according the GFDL B1 and A2 scenarios



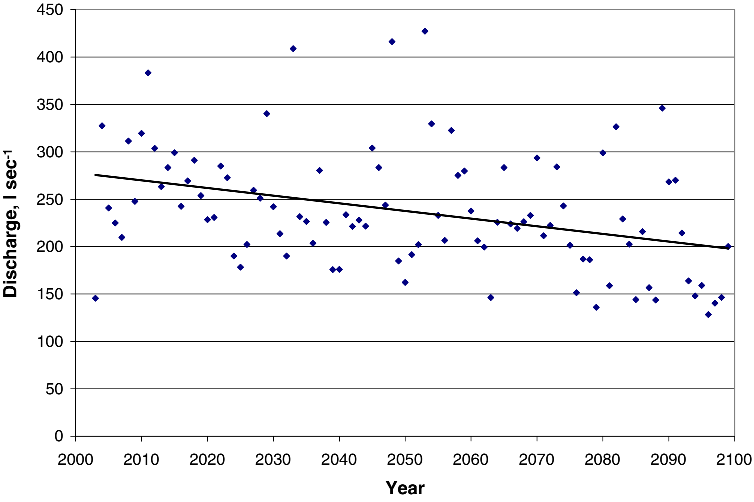
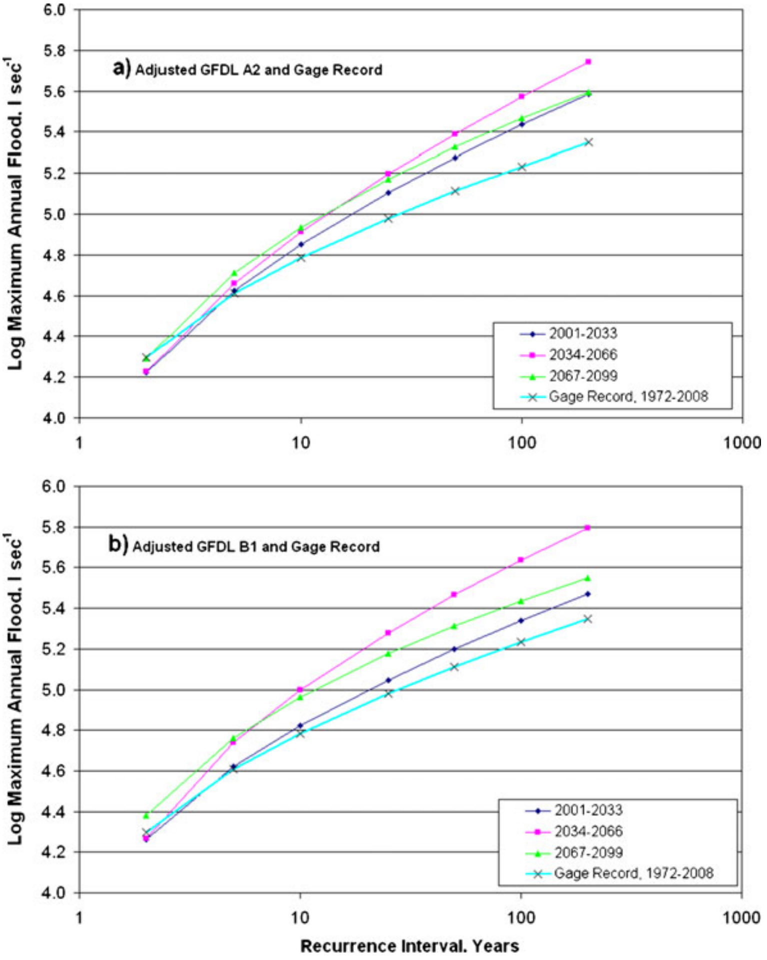


Fig. 9 Trend in the annual minimum 5-day low-flow for the UTR, for the GFDL A2 scenario

3.4 Flooding of the upper Truckee river

The UTR flood frequency curves for the two scenarios and three 33-yr periods are shown in Figs. 10a and b, and the percent change for each from the historic gage record is shown in Fig. 11a and b. The greatest impact of climate change on the future flood frequency estimates is for the mid-century under the B1 scenario. For that time period and scenario, the 100-yr flood is projected to increase 2.5-fold. The flood that is now expected 1 year in 100–170 m^3 sec^{-1}— will (for the middle third of the century) be expected about 1 year in 21. This is consistent with the GFDL/LSPC results, which show that the reduction in snowpack depth and duration in the middle third of the century (averaged over the Tahoe basin) is actually greater for the B1 than for the A2 scenario. In the latter, the snowpack depth and duration in the middle third of the century are greater than in the first or last thirds of the century (Riverson 2010). The decline in 100-yr flood magnitude in the A2 scenario toward the end of the century coincides with declining precipitation.



a) Adjusted GFDL A2 and Gage Record

b) Adjusted GFDL B1 and Gage Record

Fig. 10 **a-b** Adjusted flood frequency curves from the GFDL/LSPC B1 and A2 scenarios, for the periods 2001–2033, 2034–2066 and 2067–2099, along with the historic curve from the gage record

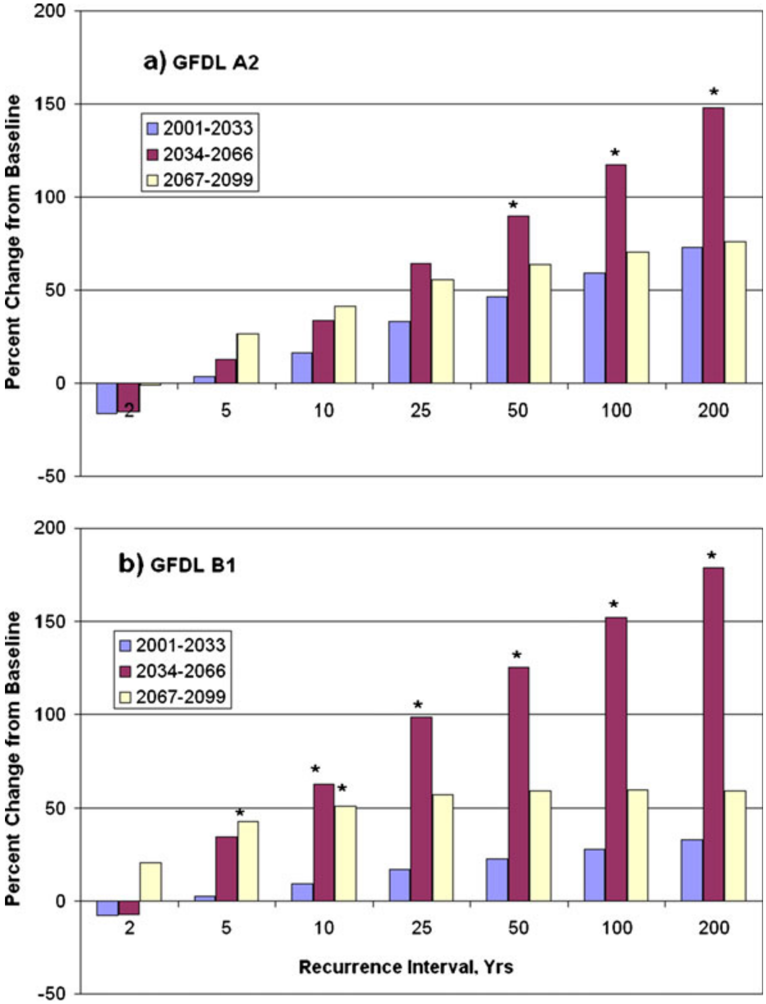


Fig. 11 **a**-**b** Percent change in the modeled and adjusted GFDL/LSPC B1 and A2 flood frequency curves from the gage record (1972–2008). * indicates that the change from the historic baseline is significant at the 90% level or greater.

Das et al. (2011) used three different GCMs (including the GFDL CM2.1) together with the Variable Infiltration Capacity model to examine the effects of climate change (under the A2 emission scenario) on frequency of the three-day flood in northern California. They found that the percentage increases in flood magnitude were greatest for the larger, less-frequent floods, with a 40% increase in the 50-yr flood for the 2001–2049 period over the same frequency flood for the 1951–1999 period. They attributed the increasing flood frequencies to increases in the size of the largest storms, increased storm frequencies, and the shift from snowfall to rain. Consistent with our results, they found (with the GFDL) a decline in flood magnitude in the latter half of this century, associated with decreasing precipitation. Their cautionary note that their results "cannot be interpreted as prediction of flood changes but rather as examples of levels of flood change that could plausibly develop in the 21st century" applies to our results as well.

3.5 Future research needs

This study has shown that anthropogenic greenhouse warming is likely to have complex effects on the hydroclimatology of the Tahoe basin. The results suggest a number of directions for future inquiry, the results of which may help inform future adaptation to climate change in the basin. These include:

- *Extending streamflow statistics to other gaged streams in the Tahoe basin.* In this study we focused on the Upper Truckee River, since it is the largest tributary of Lake Tahoe. The LSPC results, however, show considerable variability in changes to precipitation patterns throughout the basin. It would be useful to analyze projected changes in flood frequency, low-flow, flow duration and annual streamflow for the other nine gaged tributaries in the basin, using the historic records for bias correction. The results might show some interesting differences among watersheds, as Null et al. (2010) found for 15 river basins on the west slope of the Sierra Nevada.
- *Impacts of adaptive water resource management on the surface elevation of Lake Tahoe.* The level of Lake Tahoe is influenced not only by runoff and annual evaporation, but also by the operation of the outlet at Tahoe City. The operation in turn is determined by supply and demand in the entire Truckee River Basin, under the Truckee River Operating Agreement (TROA). The RiverWare model (Zagona et al. 2001) used to support TROA could be modified to incorporate scenarios of climate change and to explore how changing water supply and demand throughout the Basin might affect the level of Lake Tahoe.
- *Geomorphic impacts of climate change on streams in the Tahoe basin*. The future changes in flood frequency for the Upper Truckee River indicated in this study have major implications for channel erosion, stream morphology and riparian zone management. Simon et al. (2003) employed the CONCEPTS model to help evaluate streambank erosion in the Tahoe basin. The streamflow output from the LSPC could be used as input to CONCEPTS model to evaluate the potential impact(s) of anticipated changes in flood frequency on channel erosion, sediment loss from stream channels and the stability and function of riparian ecosystems.
- *Impacts of climate change on the climax vegetation of the Tahoe basin.* The coming changes in temperature, precipitation and drought indicated in this study will ultimately have major impacts on the vegetation of the Tahoe basin, but the rate and direction of vegetation change are uncertain. Detailed vegetation and soils maps of the basin have been developed (e.g., Dobrowski et al. 2005), and sub-kilometer scaled maps of recent and projected future temperature and Climatic Water Deficit are now available (Flint and Flint 2012). These maps (in GIS format) could be used together with existing vegetation models to produce maps of future vegetation for the basin under the two emissions scenarios. The projected vegetation changes might then be used in the LSPC to examine possible impacts of vegetation change on erosion and sediment yield.

4 Conclusions

Downscaled climatic data from two General Circulation Models (the GFDL and PCM) and two emissions scenarios (B1 and A2) have been used to constrain projections of 21st century temperature and precipitation in the Tahoe basin. For the GFDL, downscaled output has also included daily wind, relative humidity and downward long-wave radiation. The meteorological data were corrected for bias and adjusted to local temperature, precipitation and wind data, and the results were used to drive a distributed hydrology model and a lake mixing model. The output from the hydrology model has been used to analyze future projected trends in the Palmer Drought Severity Index, and the fraction of precipitation falling as snow. For the Upper Truckee River, the hydrology model was also used to analyze the trend in timing of the annual hydrograph centroid, the shifts in the flow-duration curves and flood frequency curves, and the trends in the annual minimum 5-day low flow and total annual water yield.

The results show 1) upward trends in average annual T_{max} and T_{min}, with trends for the GFDL>PCM, and trends for the A2>B1; 2) some trends in monthly and annual precipitation amount, especially declining precipitation for the GFDL A2 case toward the end of the century; 3) a continuing shift from snowfall to rain, and toward earlier snowmelt and runoff during the water year, for both scenarios; 4) a downward shift (to lower discharge for a given exceedance frequency) in the flow-duration curve for the A2 scenario in the last third of the century; 5) declining minimum 5-day low-flow for the A2, but not for the B1 case; 6) increasing aridity in the 1st half of this century under the B2 scenario, and in the latter half of the century under the A2 scenario; 7) For Lake Tahoe's largest tributary, dramatic increases in flood magnitude in the mid-century period, especially with the B1 scenario.

These changes will create stresses on both terrestrial and aquatic ecosystems in the Basin, and pose serious challenges to resource managers, especially in the latter half of this century. These challenges include increased risk of wildfire, increased tree mortality from insects and disease, increased erosion and sediment production, and alterations to aquatic, wetland and riparian habitat.

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