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Projecting impacts of climate change on surface water temperatures of a large subalpine lake: Lake Tahoe, USA

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Abstract Predicted increases in atmospheric CO_2 concentration are expected to cause increases in air temperatures in many regions around the world, and this will likely lead to increases in the surface water temperatures of aquatic ecosystems in these regions. Using daily air and littoral water temperature data collected from Lake Tahoe, a large sub-alpine lake located in the Sierra Nevada mountains (USA), we developed and tested an empirical approach for constructing models designed to estimate site-specific daily surface water temperatures from daily air temperature projections generated from a regional climate model. We used cluster analysis to identify thermally distinct groups among sampled sites within the lake and then developed and independently validated a set of linked regression models designed to estimate daily water temperatures for each spatially distinct thermal group using daily air temperature data. When daily air temperatures projections, generated for 2080–2099 by a regional climate model, were used as input to these group models, projected increases in summer surface water temperatures of as much as 3 °C were projected. This study demonstrates an empirical approach for generating models capable of using daily air temperature projections from established climate models to project site specific impacts on littoral surface waters within large limnetic ecosystems.

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Abbreviations

SWT Surface water temperature

OEI Offshore and exposed inshore

EI Enclosed inshore

1 Introduction and background

Surface water temperatures of freshwater ecosystems will respond strongly to anticipated increases in global atmospheric temperatures (Robertson and Ragotzkie 1990; Hondzo and Stefan 1993). Warmer water temperatures can lead to significant changes in the physical (e.g. water clarity, and ice cover), chemical (e.g. pH and nutrient availability, dissolved oxygen level) and biological (e.g. growth and persistence of organisms, invasive species establishment) processes and attributes of freshwater lake systems (Shuter and Meisner 1992; Schindler 2001; Rahel and Olden 2008). Projecting how water temperatures of lake systems will respond to climate change can be useful for anticipating and mitigating the ecological impacts of climate change on these systems. However, to date climate change projections for freshwater systems have focused on among-lake differences across large regional landscapes (e.g. Sharma et al. 2007; Trumpickas et al. 2009)—methods incorporating downscaled models operating at smaller spatial scales, or within large lake systems, are rare.

In this study, Lake Tahoe (39°6′N, 120°6′W), a large (avg. depth: 305 m, surface area: 500 km^2) oligotrophic, subalpine (1,898 m above sea level) lake (Fig. 1), situated on the borders of California and Nevada, is used as a case study to explore an empirical method for projecting within lake, site-specific nearshore future surface water temperatures (SWTs - Moyle 2002). Lake Tahoe is a suitable case study system for several reasons. Firstly, locations inland or at higher elevations may be climatically more vulnerable and should have greater temperature and precipitation responses to climate change than coastal locations, or areas at lower elevations (Snyder et al. 2002). Secondly, studies exploring possible future climates in California have generally projected air temperature increases ranging from 1 to 6 °C by 2,100, depending on the greenhouse gas emission scenario used and time period set by the climate model (Kim 2001; Hayhoe et al. 2004; Duffy et al. 2006). For example, down-scaled output of the Geophysical Fluid Dynamics Laboratory global climate model (GFDL CM2.1: A2 scenario) shows a 4–5 °C increase in Tahoe basin's air temperature over the 21st century (Coats et al. 2013). Thirdly, a general warming trend has already been documented for Lake Tahoe: over the period 1992–2008, mean summer water temperatures have been increasing at a rate of 0.11 °C per year (Schneider et al. 2009). Finally, Lake Tahoe is an important national resource, especially for the two western states it borders; the lake is an important source of freshwater for residents in the surrounding area and the extraordinary clarity of its water has made it one of three water bodies in the western United States to be designated an Outstanding National Resource Water under the Clean Water Act (TRPA 2009). Thus, assessing potential impacts of climate change on the littoral waters of Lake Tahoe is of national interest, as well as of interest to many local stakeholders.

The primary objective of this paper is to present a method for constructing empirical models designed to estimate downscaled, site-specific future water temperatures from future air temperatures generated by a regional climate model. Instead of generating lake-wide averages, this modeling approach takes into account the temporally consistent, spatial heterogeneities in SWT that are often found in large lakes (e.g. Finlay et al. 2001). Using several historical air and SWT datasets available for Lake Tahoe, we tested the effectiveness and practicality of the proposed

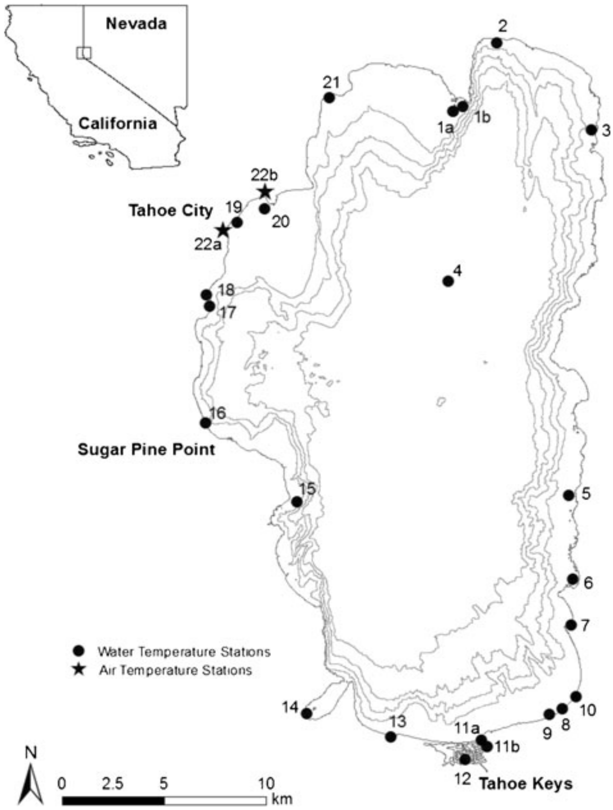

Fig. 1 Map of Lake Tahoe, California-Nevada (with bathymetry shading), showing locations of water (*Black circle*) and air (*Black star*) temperature sampling stations. See Tables 1 and 2 for detail descriptions of sampling stations

modeling approach. We assessed the potential impact of climate change on Lake Tahoe littoral waters by projecting future SWTs in the period 2080–2099 under a selected climate change scenario. The modeling framework presented here should be applicable to other lake systems where historical air and water temperature records are available. Outputs generated should be useful for assessing thermally related ecological concerns, such as the degree to which future changes in local water temperatures will permit invasions by exotic species.

2 Model development

This empirically based study relies on historical air and water temperature data from Lake Tahoe to accomplish the following: (i) identify spatially distinct thermal regions in the lake; (ii) construct regression models linking observed air temperatures to observed water temperatures in those regions; (iii) permit independent assessment of the accuracy of the regression models once they are built. Fortunately, there are significant collections of air and water temperature data from Lake Tahoe and its surroundings that extend over several decades. The time scale and methods of data collection are similar across data sets, with the overall accuracy sufficient to characterize daily variation of the order of~1 °C (Coats et al. 2006, Table 1). Some methodological inconsistency is common in studies based on historical reconstructions of data time series. We have examined and compared the different datasets vigorously and used the data conservatively in our analyses. We believe that our study

Table 1 Summary of temperature time series data used in this study

Dataset ID code	Type of temperature data	Role in model development	Length of time series	Sampling period within each year	Sampling frequency and data acquired
W6795	Water	Validation	1967–1995	March–Dec	1–3 times per month, one measurement taken at midday
W9603	Water	Calibration	1996–2003	May–Dec	Biweekly, one measurement taken at midday
W03	Water	Calibration	2003	June–Nov	Daily mean, from measurements at 2-h interval
W06	Water	Validation	2006	April–Nov	Daily, measurement at 3-h interval
A1003	Air	Reconstruction	1910–2003	Jan–Dec	Daily mean, from approx hourly measurements
A6795	Air	Validation	1967–1995	Jan–Dec	Daily mean, from approx hourly measurements
A9603	Air	Calibration	1996–2003	Jan–Dec	Daily mean, from approx hourly measurements
A06	Air	Validation and Reconstruction	2006	Jan–Dec	Daily mean, from approx hourly measurements
RCMModern	Air	Projection	1980–1999	–	–
RCMFuture	Air	Projection	2080–2099	–	–

provides a sound demonstration of how to compensate for such inconsistencies and generate useful results.

2.1 Temperature data sources

Four SWT and air temperature datasets collected between 1967 and 2006 were compiled from several academic and government institutional sources for use in the model development process (Table 1).

For the period 1967 to 1995, point-in-time SWTs (data set W6795, Table 1) were recorded 1 to 3 times a month, in daytime at a depth of ~0.75 m, at two sites on the lake (Fig. 1 and Table 2, station 17 and 4 respectively). For the period 1996 to 2003, point-in-time SWTs (data set W9603, Table 1) were recorded biweekly at midday at 1 m depth at the same two sites. In 2003, daily mean SWTs (data set W03, Table 1) were calculated from 12 readings taken every 2 h from June through November at depths of 0.75–1 m at 10 stations around the lake (Fig. 1, Tables 1 and 2) using Onset Stowaway™ temperature loggers. In 2006, daily mean SWTs (data set W06 Table 1) were calculated from daily maximum and minimum SWTs from April through November at depths of 0.75–1.0 m at 28 sites around the lake (Fig. 1, Tables 1 and 2) using i-button™ temperature loggers. The temperature observation stations used in 2003 and 2006 fall into three categories: 1) offshore, 2) exposed inshore, and 3) enclosed inshore. Offshore stations are generally located on offshore buoys,

Table 2 Summary of sampling station information. (Refer to Fig. 1 for physical locations of stations)

Station number	Station location	Station description	Cluster group	Water temp set				Air temp set
				W03	W9603	W6795	W06	
1a	Northern Stateline	Offshore	OEI	X			X	
1b	Northern Stateline	Offshore	OEI				X	
2	Crystal Bay Cove	Exposed inshore	OEI	X			X	
3(a&b)	Sand Harbor	Offshore, exposed inshore	OEI				X	
4	MLTP	Offshore	OEI	X	X	X	X	
5	Cave Rock	Offshore	OEI				X	
6(a&b)	Zephyr Cove	Offshore, exposed inshore	OEI	X			X	
7	Round Hill Pine	Intermediate	INT				X	
8(a&b)	Ski Run	Intermediate	INT				X	
9	Timber Cove	Intermediate	INT				X	
10	Lakeside	Intermediate	INT				X	
11	Tahoe Keys East	Enclosed inshore	EI	X			X	
12	Tahoe Keys West	Enclosed inshore	EI	X			X	
13(a&b)	Taylor Creek	Exposed inshore	OEI				X	
14	Emerald Bay	Exposed inshore	OEI	X			X	
15	Sugar Pine Point	Offshore	OEI	X			X	
16	Obexer's	Exposed inshore	OEI				X	
17	LTP	Exposed inshore	OEI	X	X	X	X	
18	Sunnyside	Exposed inshore	OEI	X			X	
19(a&b)	Tahoe City	Exposed inshore	OEI	X			X	
20	Lake Forest	Exposed inshore	OEI	X			X	
21	Carnelian Bay	Exposed inshore	OEI				X	
22a	Tahoe City NOAA Coop station (prior to 1950)	Air Temperature	–					A1003
22b	Tahoe City NOAA Coop station (after 1950)	Air Temperature	–					A6795, A9603, A06

are only accessible by boat, and have water depths of ≥20 m; exposed inshore stations are in shallow (1–5 m), nearshore areas where no physical barrier separates water around the station from the main lake; enclosed inshore stations are in shallow nearshore areas that are partially isolated from the main lake by physical barriers.

Daily mean air temperatures were calculated from the records of maximum and minimum daily air temperatures collected between 1910 and 2006 (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?WWDI~StnSrch) at the Tahoe City NOAA weather station. Data gaps of air temperatures fewer than 3 days were filled by linear interpolation. Periods with gaps of more than 3 days were not included in our analyses. This time series was subdivided into 4 shorter data sets (Table 1), each having a *separate* role in the overall model building process. The weather station is currently located in Tahoe City, CA (NOAA Coop Station 048758, Station 22b -Fig. 1); prior to 1951, it was located nearby (Station 22a-Fig. 1).

2.2 Identifying spatial heterogeneity in water temperatures

Spatial heterogeneity in SWTs is typical in large lakes (e.g. Finlay et al. 2001) and needs to be quantified when developing within lake-scale empirical SWT projection models. We used variation analysis and cluster analysis of the concurrent, site-specific daily water temperature time series from both 2003 and 2006 to identify temporally consistent spatial heterogeneity in SWTs across Lake Tahoe.

We used variation analysis to quantify seasonal changes in the range and standard deviation of daily mean SWTs recorded across all sampled sites. We used cluster analysis to determine if this variation was the product of temporally consistent spatial heterogeneity among sites. To facilitate partitioning and to minimize the effect of missing data, we focused our cluster analyses on the season identified by variation analysis as the season where among-site SWT variation was greatest. We used the agglomerative hierarchical method and Euclidean distances, as embodied in the AGNES programming function in S-PLUS™ (see S-PLUS help manual for detailed description of the program—Kaufman and Rousseeuw 1990). Results from both complete linkage (furthest neighbour) clustering and UPGMA (Unweighted Pair Group Method with Arithmetic means) clustering were considered (Legendre and Legendre 1998; Gordon 1999). Consensus tree analysis (Gordon 1987) and the CI(C) index (Rohlf 1982; NT-SYS numerical-taxonomy package; Rohlf et al. 1982) were used to assess dendrogram similarity. The Majority-Rule Consensus tree (Gordon 1987) and the CI(C) index (Rohlf 1982; Jackson et al. 1989) both measure agreement between dendograms. CI(C) values can range between 0 and 1 (Rohlf 1982; Jackson et al. 1989).

In both 2003 and 2006, spring and early summer was the period of greatest spatial variation in SWTs—a finding similar to that reported by Finlay et al. (2001). We used cluster analysis on data from the period in each year when both the range and standard deviation of across-site temperatures were near their maximum values (Julian day 158–195 for 2003 and 166–213 for 2006) and we observed a consistent clustering of sites in both years. There were 3 thermally distinct clusters (Fig. 2): (i) enclosed inshore (EI) sites - located within the Tahoe Keys (the largest marina complex located in the south side of the lake- Fig. 1 and Table 2, station 11a,b and 12); these sites were consistently warmer in late spring-early summer and cooler in the fall than the other sites; (ii) offshore and exposed inshore (OEI) sites - located offshore, or inshore on exposed shorelines; these sites were consistently cooler than other sites in spring and summer, and warmer in fall; 3) intermediate (INT) sites - located mostly along the southern shore; these sites exhibited intermediate temperatures in all seasons. We used two clustering methods on the same sets of data, (i.e. UPGMA and complete linkage clustering) to verify that the groupings identified were robust to the choice of clustering method. For W03 and W06, both the consensus tree analysis and the consensus index (CI(C) =1.0 and 0.84 respectively) indicated that the dendrograms from the two methods were similar and consistent.

2.3 Modeling spatial heterogeneity in water temperatures

We focused our modeling work on constructing SWT projection models for the OEI (coolest spring and summer, warmest fall) and EI (warmest spring and summer, coolest fall) clusters of sites, with the intent of capturing the full range of horizontal thermal variability likely to be observed under climate change.

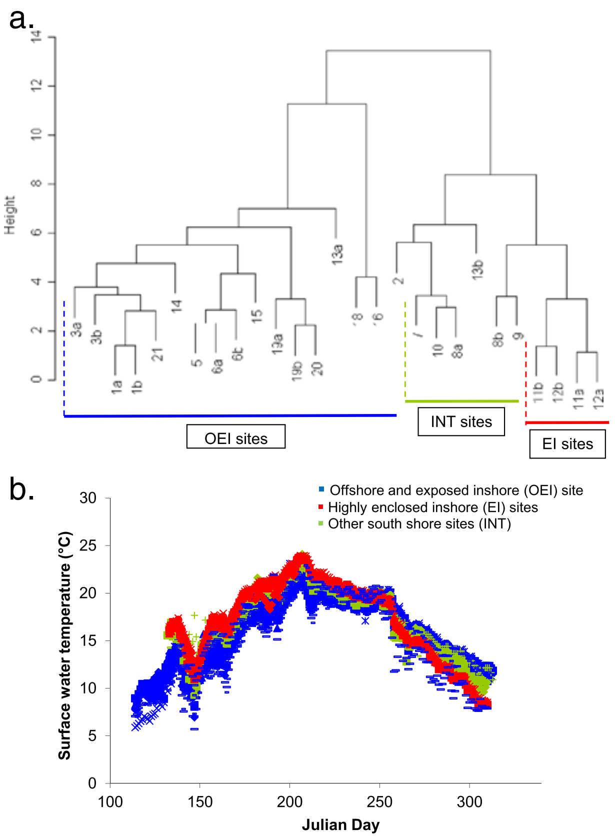

Fig. 2 **a** Dendrograms (Cluster Analysis) of 2006 late spring/early summer (Julian day:166–213) daily surface-water temperatures (SWT) at various sites across Lake Tahoe based on Unweighted Pair Group Method with Arithmetic means (UPGMA). The dissimilarity between sites in terms of daily SWT can be determined from the height at which various sites are joined into groups. See Fig. 1 for site locations. **b** 2006 daily SWT from early spring to late fall collected by 27 temperature probes at 21 sampled sites. *Blue* represents temperature regimes of offshore and exposed inshore (OEI) sites, *red* represents temperature regimes of highly enclosed inshore (EI) sites (i.e. Tahoe Keys at the south side of the lake), and *green* represents other south shore sites INT)

2.3.1 OEI base model development and validation

Models for predicting SWTs from air temperatures are common in the literature (e.g. Shuter et al. 1983; Livingstone and Lotter 1998; Kettle et al. 2004) and several (Matuszek and Shuter 1996; Groeger and Bass 2005; Livingstone and Padisak 2007) demonstrate that daily SWTs can be accurately predicted using various combinations of lagged running averages of daily air temperatures. We followed Matuszek and Shuter (1996) because their model is simple and was validated with data from several (14) lakes covering a wide range of areas, depths and shapes. Matuszek and Shuter (1996) also demonstrated that air temperatures used for their model input need not be collected at a point close to the lake, as long as it is within the same regional climatic zone as the lake (e.g. within~300 km for the lakes they examined). The SWT model for a particular thermal cluster of sites has the following structure:

$$SWT_{yday} = C_0 + C_1(ATemp5) + C_2(ATemp20) + C_3(yday) + C_4(yday)^2 \qquad (1)$$

where SWT_{yday} is the daily mean SWT (°C) on Julian day *yday*, C_{0-4} are cluster-specific constants, ATemp5 is the 5-day running mean of daily average air temperatures (°C) for the 5 day period ending with *yday*, and ATemp20 is the 20-day running mean of daily average air temperature (°C) for the 20 day period ending with *yday*. In the original formulation of the model, Matuszek and Shuter (1996) included an additional term to allow for the effects of ice cover. However, Rennie (2003) reported that this term was not significant in his application of the model, and Lake Tahoe does not freeze over (Jassby et al. 2001; Coats et al. 2006), thus this term was not included in our model.

The Matuszek and Shuter (1996) model was designed to capture the empirical linkage between SWTs and air temperatures, when daily SWTs fluctuate in response to the annual rise and fall of air temperatures in the "non-winter period" of a year. Therefore, the model is not appropriate for projecting SWTs during winter, when Tahoe water temperatures stabilize and become relatively independent of air temperature. In our case study, we defined the non-winter period as the period when daily SWTs are consistently above the winter threshold temperature of 4.6 °C. This threshold temperature was selected based on long term lake monitoring records which show that, during winter, Lake Tahoe SWTs remain at~4.6 °C despite changes in winter air temperatures (Strub and Powell 1987; Jassby et al. 2001).

We used linear regression to fit OEI SWT data (data sets W9603 and W03, pruned to include only values from the non-winter period and averaged across OEI sites within a day) to Tahoe City air temperature data (dataset A1003) and generated the following OEI base model (R^2=0.93; RMSE=0.88; N=312; RMSE values for individual years range from 0.66 to 1.35):

$$SWT_{yday} = -20.6783 + 0.16255(ATemp5) + 0.29978(ATemp20) + 0.26121(yday) - 5.35E^{-4}(yday)^2 \qquad (2)$$

We validated this model using two independent SWT datasets (W6795 and W06), one from an historical period (1967–95) prior to that used to derive the model (1996–2003) and the other from a period (2006) subsequent to that used to derive the model. Validation results for both time periods demonstrated that, overall, the OEI model provided unbiased predictions of daily temperatures (Fig. 3a), with relatively small and consistent within- and between-year error levels: (i) for the 1967–1995 period, overall mean residual=0.0482 °C; range for yearly mean residuals (N=29): −0.94 to 0.89 °C; range for yearly RMSE values: 0.73 to 1.87; 85 % of all daily forecasts (N=569) were within +/−1.5 °C of observed values (ii) for 2006, RMSE=0.89; 90 % of all daily projections (N=148) were within +/− 1.5 °C of observed values. However, the monthly residual plot (Fig. 3b) does reveal that the accuracy of model predictions is reduced for those periods (March, April and November) when SWTs are just rising from, or closely approaching the winter threshold temperature. For these months, some residual values were derived from predicted values that were set to 4.6 °C because the raw values from Eq. (2) were<4.6C.

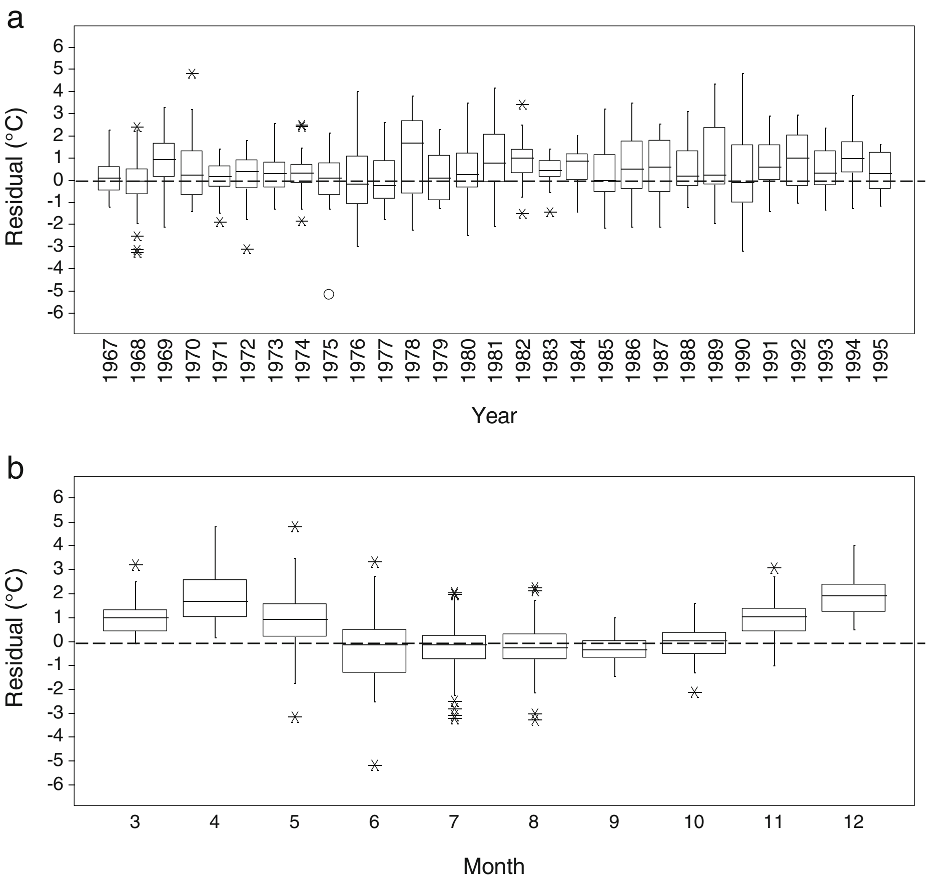

Fig. 3 Historical reconstruction testing (1967–1995): Residual temperatures (observed-predicted) summarized for (**a**) annual and (**b**) monthly time frames. Predictions were generated using OEI base model and daily air temperatures recorded in 1967–1995, and were compared to observed offshore and exposed inshore (OEI) water temperatures collected in 1967–1995. The *lines* in the boxes represent the 25 %, 50 % and 75 % quartiles. Extreme values are displayed as "*Asterisk*" for possible outliers (exceeds box boundaries by more than 1 1/2 times the height of the box) and "O" for probable outliers (exceeds box boundaries by more than 3 times the height of the box)

2.3.2 EI model development and validation

Since only 2 years (2003, 2006) of data were available from EI sites, we could not follow the same modeling approach as we used for OEI sites. However, for those years where concurrent OEI and EI data were available, mean daily EI SWTs were linked to mean daily OEI SWTs by strong, but distinctly different, linear relationships during the spring warming period (R^2=0.59) and the fall cooling period (R^2=0.98). Within each season, there were relatively small (but statistically significant ANCOVA spring p=0.03 and fall p<0.001) interannual differences in the parameter estimates for these regression lines: (i) For Spring, 2003 and 2006 slope values were 0.6984 and 0.9318 respectively, the pooled slope was 0.8946 and, overall, the 2003 relationship was elevated above the 2006 relationship such that, for any given OEI value, the 2003 EI value was~1 °C higher than the 2006 EI value;

(ii) For Fall, 2003 and 2006 slope values were 1.6002 and 1.7782, respectively, the pooled value was 1.7252 and, overall, for any given OEI value, the 2003 EI value was similar to the 2006 EI values. Given these results, we chose to model EI SWTs using values from the OEI base model as input to two separate linear relationships, one linking spring EI values to spring OEI values and the other linking fall EI values to fall OEI values, with the day of the year with the highest OEI SWT value (HTD) used to separate the spring warming and fall cooling phases of the year. Regression analysis of the pooled 2003 and 2006 data was used to derive the final model (R^2=0.8 and 0.85, Mean residual=0.3 °C and 0.22 °C, RMSE=1.39 and 1.33, for 2003 and 2006 respectively):

$$\begin{aligned} SWT(yday)_{EI(warming)} &= 0.8946\ SWT(yday)_{OEI(all\,yday \leq HTD)} + 5.6391 \\ SWT(yday)_{EI(cooling)} &= 1.7252\ SWT(yday)_{OEI(all\,yday \geq HTD)} - 12.5718 \end{aligned} \tag{3}$$

where: $SWT(yday)_{EI}$ is the predicted daily EI SWT value for Julian day *yday* ; $SWT(yday)_{OEI}$ is the OEI SWT value generated from the OEI base model for *yday* and HTD is the Julian day where $SWT(yday)_{OEI}$ reaches its maximum value.

An independent EI SWT dataset from 2001 was used to validate the EI model. The R^2 value between observed and predicted values was high (0.84) while both mean residual and RMSE value (0.875 °C and 2.13) were only moderately higher than the RMSE and residual values for 2003 and 2006.

3 Model applications

3.1 Reconstruction of current SWTs and projection of future SWTs

We used observed daily air temperature data (1910–2006) collected from Tahoe City weather station to reconstruct historical daily SWTs using the calibrated and validated empirical models. Projected (2080–2099) daily air temperatures generated by the regional climate model (RCM) published in Snyder and Sloan (2005) were used to derive future SWT projections for Lake Tahoe under one climate change scenario. The projected air temperature data were provided by Dr. Mark A. Snyder from the Department of Earth and Planetary Sciences, University of California, Santa Cruz.

3.1.1 Future climate change scenario

In Snyder and Sloan (2005), possible changes in California climate for the period from 1980–99 (the ‘Modern’ period) to 2080–99 (the ‘Future’ period) were examined using the RCM - RegCM2.5. The output from an atmosphere—ocean general circulation model (AOGCM)—National Center for Atmospheric Research (NCAR) Climate System Model version 1.2 (see Snyder and Sloan 2005 for model details) was used to drive the RCM. For the AOGCM runs, CO_2 concentrations were updated each year based on 1) observed values of greenhouse gases (338–369) for the “Modern” case, and 2) projected values from the IPCC A1 scenario for the “Future” case. The CO_2 values used in the RCM for “Modern (1980–99)” and “Future (2080–99)” cases were fixed at 353 and 660 ppm respectively, as the RCM cannot handle time-varying greenhouse gases (Snyder and Sloan 2005). Snyder and Sloan (2005) demonstrated that the RCM reproduced reasonably accurate monthly average temperature values for the Modern period, with an average underestimation of approximately 2 to 4 °C. It was also able to capture the seasonal cycle of temperatures for all months examined.

This RCM provides output at a much higher resolution (40 km×40 km) than a typical global climate model (GCM) (~280 km×280 km), and is better at capturing regional variation in climate, especially for areas like California which are topographically complex (Bell et al. 2004; Snyder and Sloan 2005). Four grid cells from the RCM cover the entire range of Lake Tahoe. We compared past air temperatures (1980–1999) collected from the Tahoe City weather station with simulated air temperatures generated by the RCM for the same time period to identify the grid cell output that was most comparable to observed Tahoe City values.

Before future air temperature projections generated from the RCM could be used as input for our SWT projection models, pre-treatment of the raw RCM output was required to address the following limitations of RCM model: (i) daily variation in simulated RCM air temperature values tends to exceed observed variation due to numerical properties of the simulation algorithms (M. A. Snyder, University of California- Santa Cruz, personal communication); (ii) systematic bias in simulated values can be present due to inherent discrepancies in the GCM output that drives the RCM (Snyder et al. 2002); (iii) each grid temperature value from the RCM represents the average temperature within a 40×40km grid cell, thus variation at smaller spatial scales cannot be captured accurately by the RCM model. We dealt with these limitations by (i) using a 5 day running average (running mean of a 5 day period ending with the current day) of the simulated RCM daily air temperatures as input to our empirical models to reduce the simulated daily variations to values comparable (< 30 %) to observed daily variations; (ii) applying to these daily running averages, a correction factor based on the monthly median differences between observed and simulated air temperatures for the 1980–99 "modern" period.

3.1.2 Future SWT projections for Lake Tahoe

Daily SWT projections generated by the OEI base model and the supplementary EI model were summarized as annual averages (Fig. 4). Winter values were generated by enforcing a minimum

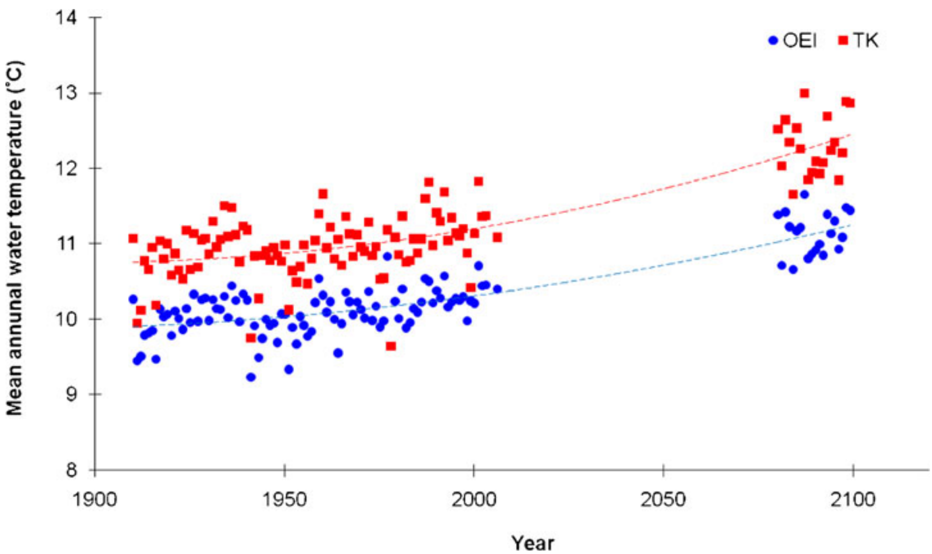

Fig. 4 Past, present, and future mean annual surface-water temperature projections (°C) for exposed sites (OEI, *blue circle*) and enclosed sites (TK, *red square*) in Lake Tahoe

value of 4.6 °C on all daily projected values below 4.6 °C for both OEI and EI models. Based on our selected climate change scenario of 660 ppm CO_2 by 2080–2099, we projected an increase of ~1.5 °C in mean annual SWTs for the OEI sites (Fig. 4) and an increase of ~2 °C for EI sites. By 2080–2099, some EI and OEI sites will have daily mean SWTs as high as 26 °C (present maximum ~23 °C) and 23 °C (present maximum~20 °C) respectively, in summer months.

These projected increases for future SWTs continue a consistent trend of increasing SWTs that is evident in the historical reconstruction of SWTs for the period 1910–2003 (Fig. 4).

4 Discussion

4.1 Model performance

In this study, our objective was to develop empirical models for reconstructing historical, or projecting future, Lake Tahoe water temperatures from air temperature data. Earlier studies (Strub and Powell 1987) had demonstrated the existence of temporally consistent, spatial heterogeneity in Lake Tahoe SWT's: from early spring to late summer, temperatures tended to decrease from east to west. This was attributed to frequent upwelling events on the west side of the lake. Our observations extend these findings, identifying sets of inshore sites that warm and cool much faster than others. These sites were located in shallow, semi-enclosed embayments, often the product of shoreline development (e.g. marina construction), which reduced inshore-offshore mixing. We characterized these patterns of spatial heterogeneity in SWTs by classifying areas of Lake Tahoe into several temporally consistent, distinct thermal groups and then building linked projection models for the warmest and coldest of these groups. The effectiveness of these empirical models matched (range for R^2 values: 80 % to 93 %) that achieved (87 %) by the mechanistic model of Coats et al. (2006) for a similar time frame. Validation results for our empirical models (~85 to 90 % of predicted daily values fell within +/− 1.5 °C of observed values) confirmed that they are reasonably effective at capturing the site-specific links between daily air temperatures and SWTs. However, like all empirical models, there are inherent limitations to their accuracy: (i) the model structure assumed by Matuszek and Shuter (1996) was designed to capture the seasonal rise and fall of SWTs and thus is not appropriate and should not be used for predicting SWTs during winter conditions, when SWTs remain relatively stable regardless of changing air temperatures; (ii) model reliability is tied to the range of conditions covered in the calibration and validation data sets; extrapolation beyond these ranges could produce less accurate predictions.

The future SWT projections generated by our models depend on the future air temperatures projection we used as model inputs. Different future air temperature projections can be generated by (i) different combinations of the GCM and RCM models used to generate them; (ii) different emission scenarios used to drive the GCM-RCM models (Snyder and Sloan 2005). Therefore, full exploration of the range of possible future climates for Lake Tahoe would require multiple runs of different GCM/ RCM combinations with different emission scenarios (e.g. down-scaled GCMs output used in Coats et al. 2013). Our models can serve as simple tools for quickly and accurately assessing how each of the many possible future Tahoe climates will affect SWTs across the lake.

Many modeling studies of climate change impacts on limnetic ecosystems have dealt with among-lake, landscape level heterogeneity in seasonal water temperatures (e.g. Livingstone and Lotter 1998; Sharma et al. 2007; Trumpickas et al. 2009). Our analysis of site-specific SWT variation, within a large lake system such as Lake Tahoe, illustrates that within-lake spatial heterogeneity in SWTs can be significant. However, such variation is often difficult to describe and evaluate with mechanistic models of near and offshore hydrodynamics (e.g. Shintani et al. 2010). Our study demonstrates that, given a relatively rich historical database of observed air temperatures and SWTs, simple clustering and regression approaches can produce robust models with predictive accuracy that rivals, or exceeds, that achievable with much more complex and data demanding mechanistic models. Since local historical variation over a 10 to 15 year period often (e.g. Magnuson 1990; Snucins and Gunn 2000; Magnuson 2010) encompasses the range of 'average' atmospheric conditions projected by climate change assessments for future periods of several decades (e.g. Snucins and Gunn 2000), such an historical database should generate empirical models capable of examining localized, within-lake effects of climate change over a future time frame of at least several decades. While the focus of our study was Lake Tahoe, the modeling framework we used could be easily applied to other large lakes.

4.2 Ecological impacts of future climates

Our results suggest that Lake Tahoe SWTs have warmed since the 1900s and will continue to warm under climate change. Monthly SWTs might increase by up to 4 °C, while mean annual SWTs might increase by 1.5 °C at the cooler, more exposed OEI sites and by 2 °C at the warmer, enclosed EI sites under the climate change scenario modeled (CO_2 concentration: 635–686 ppm in 2080–2099). These changes in water temperatures will likely have significant direct and indirect physical and ecological impacts on the lake's ecosystem. For instance, a stronger thermal gradient between the epilimnion and hypolimnion may develop and lake mixing will become more difficult (McCormick 1990; Schertzer and Sawchuk 1990; Ficke et al. 2007). Coats et al. (2006) have demonstrated that recent warming of Lake Tahoe has increased the lake's thermal stability and resistance to mixing, as well as a reduction in the maximum thermocline depth in late summer/early fall (Coats et al. 2006). Reduced mixing due to recent warming has already altered Lake Tahoe's lower food web, favoring smaller diatom species (Winder et al. 2009). In the shallow inshore littoral zone, direct exposure to urban runoff, abundant algal populations, and warmer SWTs will likely lead to an increase in eutrophication. The lake is already exhibiting reductions in littoral zone water clarity due to increased algal growth caused by higher SWTs and nutrient concentrations (Reuter et al. 1983; Reuter and Miller 2000). This, coupled with the reduced oxygen dissolving capacity of warmer waters can lead to oxygen stress for fish resident in the littoral zone (Schertzer and Sawchuk 1990; Stefan et al. 1993).

Elevated water temperature will also encourage invasion and range expansion of non-native species into novel environments (Radforth 1944; Holzapfel and Vinebrooke 2005; Sharma et al. 2007; Rahel and Olden 2008). The combined effect of climate change and biological invasion can significantly impact native aquatic ecosystems (Rahel and Olden 2008). Willis and Magnuson (2006) suggested that interactions between climate change and invasive species would intensify changes in fish community composition, and greatly impact ecosystem goods and services in freshwater lakes. Based on projections from our base and supplementary models, existing warm-water invaders (e.g. largemouth bass, bluegill sunfish and black crappie - *Pomoxisnigromaculatus*) whose distributions within the lake are currently limited due to thermal restrictions, may spread and become established in other parts of the lake as SWTs increase. Spread of top predators, such as largemouth bass, can led to reductions in cyprinid species richness and abundance, or even localized extirpation of native cyprinids as observed in other water bodies (Moyle 1986; Vander Zanden et al. 1999; Whittier and Kincaid 1999; Jackson and Mandrak 2002).

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