THE WARMING OF LAKE TAHOE

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Abstract. We investigated the effects of climate variability on the thermal structure of Lake Tahoe, California-Nevada, 1970–2002, and with principal components analysis and step-wise multiple regression, related the volume-weighed average lake temperature to trends in climate. We then used a 1-dimensional hydrodynamic model to show that the observed trends in the climatic forcing variables can reasonably explain the observed changes in the lake. Between 1970 and 2002, the volume-weighted mean temperature of the lake increased at an average rate of 0.015 °C yr^{-1}. Trends in the climatic drivers include 1) upward trends in maximum and minimum daily air temperature at Tahoe City; and 2) a slight upward trend in downward long-wave radiation. Changes in the thermal structure of the lake include 1) a long-term warming trend, with the highest rates near the surface and at 400 m; 2) an increase in the resistance of the lake to mixing and stratification, as measured by the Schmidt Stability and Birge Work; 3) a trend toward decreasing depth of the October thermocline. The long-term changes in the thermal structure of Lake Tahoe may interact with and exacerbate the well-documented trends in the lake's clarity and primary productivity.

1. Introduction and Background

Lake Tahoe is a large ultra-oligotrophic lake lying at an elevation of 1898 m in the central Sierra on the California-Nevada border. The lake is renowned for its deep blue color and clarity. Due to concerns about progressive eutrophication and loss of clarity, the lake has been studied intensively since the mid-1960s, and has been the focus of major efforts to halt the trends in clarity and trophic status. The state and federal governments have recently appropriated a total of about $1 billion for water quality improvements in the Tahoe basin.

Studies on the physical limnology of the lake have included weekly to monthly temperature profiles since 1969, with surface measurements from 1964. These data afford an opportunity to examine long-term trends in the lake's thermal structure, and to relate trends to possible driving climatic variables. The purpose of this study

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is to answer the questions: is there a long-term warming trend in Lake Tahoe? If so, how is it related to climatic variables? What are the long-term ecological implications of the increasing temperature and changing thermal structure? These questions are important not only for efforts to restore and maintain the clarity of Lake Tahoe, but also for efforts to understand the linkages between climate change and lake processes world-wide.

The deep water of large lakes is an attractive place to look for a signal of climate change. While the surface and near-surface temperature reflects daily and seasonal temperature changes, this short-term "noise" is filtered out in the deep water, where temperature responds on a time scale of years or decades. The deep water is said to retain a "climatic memory" (Ambrosetti and Barbanti, 1999; Livingstone, 1993). In Lake Tahoe, the lack of annual deep mixing allows the storage of heat slowly transported downward over a period of years, with partial "resetting" of the deep water to cooler temperatures when deep mixing does occur.

Warming trends and changes in thermal structure have been identified in lakes of Europe, North America and Africa. Analysis of a 52-yr record of monthly temperature profiles in Lake Zurich showed a secular temperature increase at all depths, resulting in a 20 percent increase in thermal stability. A temperature model of that lake showed that the warming trend in the lake is most likely explained by increasing nighttime air temperature, concomitant with reduced nighttime rates of latent and sensible heat loss from the lake surface (Livingstone, 2003; Peeters et al., 2002). At Lake Mendota in Wisconsin, modeling and statistical analysis (using data from 1894–1988) showed that increasing air temperature is related to higher epilimnion (near surface) temperatures, earlier and more persistent thermal stratification, and decreasing thermocline depths in late summer and fall (Robertson and Ragotzkie, 1990). Twenty years of temperature records from the Experimental Lakes Area in Northwestern Ontario showed an increase in both air and lake temperatures of 2 °C, and an increase in length of the ice-free season by 3 weeks (Schindler et al., 1996). Modeling studies of the effects of climate warming on the temperature regime of boreal and temperate-zone lakes are consistent with these observations, predicting increased summer stratification, greater temperature increases in the epilimnion than in the hypolimnion (deep water), and increased length of the ice-free season (Elo et al., 1998; Stefan et al., 1998). Warming of Lake Tanganyika between 1913 and 2000, associated with increasing air temperatures, has increased the vertical density gradient and thus decreased both the depth of oxygen penetration and the nutrient supply in the upper mixed layer (Verburg et al., 2003).

Lake Tahoe is the largest entire lake in North America, and the most oligotrophic lake in the world for which a warming trend has been documented and related to climatic variables. It is unique in terms of the research and management efforts that have been invested in maintaining clarity and water quality.

2. Study Site and Methods

2.1. PHYSICAL CHARACTERISTICS OF LAKE TAHOE

Lake Tahoe has a surface area of 501 km^2, and a total volume of 157 km^3. Maximum depth is 500 m at maximum lake level (Gardner et al., 1998), making it the third-deepest lake in North America, and the 11th deepest lake in the world. The lake is large relative to the total drainage basin area of 1310 km^2, so its hydraulic residence time is long–about 650 yr. It never freezes, and is oligomictic, mixing completely only in years of intense spring storms (Goldman et al., 1989; Wetzel, 2001). The epilimnion and thermal stratification usually begin developing in June or early July. The 31-yr average thermocline depth (defined as the depth of maximum vertical temperature gradient) is 21 m in August, 24 m in September, and reaches 32 m in October, as the upper waters cool and mix. The photic zone extends to a depth of about 100 m, and the entire water column is oxygenated throughout the year. During years of relatively shallow mixing, heat is transferred slowly below the mixed layer by eddy diffusion and internal waves. Temperature in the deep water shows a typical "sawtooth" pattern (Livingstone, 1997), rising gradually over several years, then dropping during a deep mixing event.

Since complete mixing was first documented in 1973 (Paerl et al., 1975), the lake has mixed at least 7 times to a depth of at least 400 m. Below a depth of 200 m, the temperature gradient is very slight throughout the year, typically about $-1.6 \times 10^{-4}\,°C\ m^{-1}$. At a mean temperature of 4.6 °C, the adiabatic temperature gradient is $+10^{-5}\,°C\ m^{-1}$, and the lake is theoretically stable (Imboden et al., 1977). For this reason, the gradient of nitrate concentration as well as temperature has been used to identify mixing depth. Nitrate concentration has been measured since 1975 at 0 and 10 m, and at 50 m intervals between 50 and 450 m, whereas temperature below 100 m is measured at 100 m intervals. The maximum annual mixing depth–usually reached in March– is identified as the depth where the nitrate-N gradient measured from a depth of 10 m is $<0.02\ \mu g\ l^{-1}\ m^{-1}$. Comparing the temperature profile with the depth of the "nitricline" provides confirmation of the depth of mixing.

When Secchi disk measurements of lake clarity began in 1967, the Secchi depth averaged about 30 m, and reached a maximum of 40 m. Since then, it has declined an average of 0.25 m yr^{-1}. The greatest decreases in clarity occur in years of heavy runoff, when sediment and nutrient inflow to the lake are highest (Jassby et al., 2003). Clarity tends to increase during drought years, and during years of deep mixing, when the fine particulate material responsible for most of the light attenuation is diluted in a larger volume of water (Jassby et al., 1999). The long-term loss of clarity is also associated with increasing primary productivity, which is attributed to increasing inputs of nitrogen and phosphorus. Until the early 1980s, primary productivity in the lake was nitrogen-limited; since then, it has been increasingly phosphorus-limited (Goldman et al., 1993; Chang et al., 1992).

The water temperature of the lake during the summer is heterogeneous not only vertically but also horizontally. Satellite images show that upwelling on the west side, driven by prevailing southwest winds, creates a temperature gradient across the lake that reaches a maximum in late June and early July. There appears to be a large anticylonic gyre in the north part of the lake, and weaker cyclonic gyre in the south (Strub and Powell, 1987).

2.2. SOURCES OF DATA

Since 1969, temperature profiles have been measured at two locations in Lake Tahoe (See Figure 1). At the Index Station or "LTP Station" about 0.3 km off the west shore, temperature has been measured at depth increments of 2–15 m from the

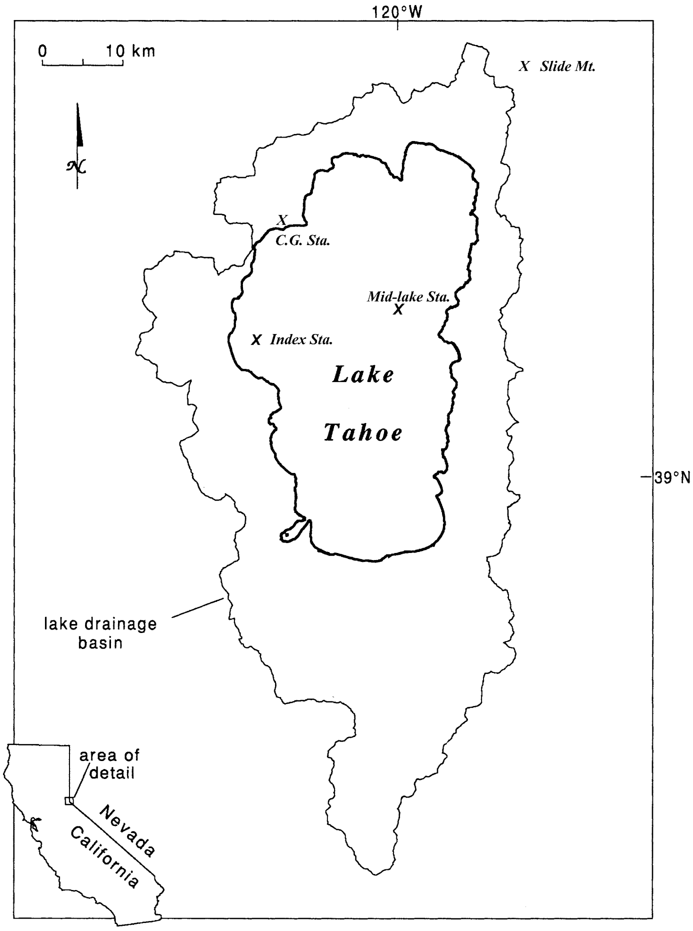

Figure 1. Map of Lake Tahoe, showing the lake sampling and meteorological stations.

surface to a depth of about 100 m approximately weekly since 1969. Temperature profiles at 1 m increments to a depth of 125 m have been measured biweekly since 1996. These series characterize the thermal structure of the epilimnion and thermocline. At the Midlake Station, (the exact location of which has varied slightly over time), temperature is measured at nominal depths of 0, 50, 100, 200, 300, and 400 m at least monthly.

Temperature in the deep-water series at the Midlake Station is measured with mercury Reversing Thermometers (RTs). A protected thermometer (unaffected by pressure) records the temperature at reversal depth, and the reading is corrected for glass expansion when the temperature is read at the surface (Sverdrup et al., 1942). A second, unprotected thermometer is affected by pressure in deep water, and (together with the corrected temperature from the protected thermometer) provides a measure of the actual depth of the temperature reading. The scales on the thermometers can be read to 0.01 °C with the aid of a magnifier. The thermometers were bench-calibrated in 1968 (at time of manufacture), in 1973, 1990 and 2003.

Temperature in the LTP series has been measured over the years with a variety of thermometers and digital thermographs. Although the sensitivity, accuracy and calibrations of these instruments have varied over time, the LTP data are adequate for characterizing the thermal structure of the epilimnion and thermocline, where temperature typically varies between 5 and 20 °C over a year.

Since the actual depth of measurement is always slightly different from the target depth, the deep water series data were filtered to include only measurements within a band around each nominal or target depth. For depths of 50, 100, 200 and 300 m, the band was $+/-10$ m of the nominal depth; for 400 m it was ± 20 m. For temperature at 0, 10, 20, and 30 m, data from the LTP and Midlake series were combined and treated together. The data set from the two series used in this study comprised 7352 temperature measurements from December 1969 to October 2002.

A record of maximum, minimum and average daily air temperature, 1914-present, is available for Tahoe City, at the northwest side of the lake (NOAA Coop Sta. 048758). The weather station was located in the village of Tahoe City until 1950, when it was moved to a Coast Guard station about 3 km northeast. Two months of missing record were filled in by regression with Truckee (15 km north), and a few missing days were filled in by linear interpolation.

Digital wind and radiation data in the Tahoe basin are not available for the entire period of interest. With funding from the California State Water Resources Control Board, a team at the University of California at Davis is using the 5th generation Mesoscale Model (MM5) of the National Center for Atmospheric Research (NCAR) to downscale the historic atmospheric data from the National Center for Environmental Prediction (NCEP) to a 3-km grid scale for the entire Tahoe basin, for the period 1958 through 2000 (Grell et al., 1994; Anderson et al., 2002). The model produces hourly values for temperature, wind, precipitation, vapor pressure, shortwave beam radiation and downward long-wave radiation, and precipitation. For statistical analysis and use in a lake temperature model, the MM5 values used were an average of the cell at Tahoe City, and at a point on the shore due east from Tahoe City. The MM5 downscaling does not produce values over large water bodies.

Solar radiation (360–200 nm) at a station on the lake's west shore has been measured with a Belfort Pyrheliograph since 1968. The daily data through 1985 have been digitized from paper charts. Since January 1986, data have been digitized only on days when primary productivity (PPr) was measured in the lake (about every 8th day). Using the days of PPr measurement, we compared the MM5 solar radiation estimate with the measured values. R^2 was 0.73 for daily values.

A consistent long-term wind record for the Tahoe basin is lacking, but wind has been measured by the authors (Perez-Losada and Schladow) on a pier near Tahoe City since 1999. Comparing the measured daily average wind speed with the MM5 data shows that the MM5 over-predicted the daily average wind by an average of 30 percent, with $R^2 = 0.53$. For mean daily temperature, however, the MM5 does much better, with $R^2 = 0.88$.

For use in the lake temperature model (described below), daily stream discharge and temperature were taken from the USGS gaging station records for 10 stations (measuring runoff from 378 km^2) in the Tahoe basin, and scaled up to the total basin area. Lake outflow was taken from records for the controlled outlet at Tahoe City, and lake bathymetry from Gardner et al. (1998). The density of the lake is only sensitive to temperature, with the effect of TDS being negligible. We used 90 mg/l, the average from 3 years of measurement at the Midlake station. Stream temperature was estimated based on a regression of streamflow, day of the year and time of day, as described in Perez-Losada (2001).

Interannual climatic variability on the west coast is known to be related to the indices of El Niño-Southern Oscillation, or ENSO (Wolter and Timlin, 1998) and the Pacific Decadal Oscillation, or PDO (Mantua et al., 1997). Positive values of the PDO are associated with warmer winters and springs in the eastern North Pacific and western North America. For statistical analysis of the Tahoe temperature data, monthly values for the Multivariate ENSO Index (MEI) were obtained from the Climate Diagnostics Center, National Oceanic and Atmospheric Administration web site (http://www.cdc.noaa.gov/kew/MEI/). The PDO Index data were obtained from the web site of the Joint Institute for the Study of Atmosphere and Oceans, University of Washington (http://tao.atmos.washington.edu/data_sets/).

2.3. REDUCTION OF DATA

For each measurement depth, daily values were interpolated for the period of record using a cubic spline (Venables and Ripley, 1996). A daily temperature profile at 1-m intervals was then derived by linear interpolation, and used to calculate total heat content and volume-weighted mean lake temperature. The daily series at depths of 0, 10, 20, 30, 50, 100, 200, 300 and 400 m were then smoothed with four-year running averages for plotting. The volume-weighted mean daily lake temperature and total heat content of the lake were seasonally-decomposed (Venables and Ripley, 1996) to remove the seasonal cycle prior to statistical analysis. Annual means of temperature and total heat were calculated for trend analysis. Time trends of the monthly means of (undecomposed) average lake temperature were calculated to examine seasonal differences in the long-term lake temperature trend.

Inspection of the 4-yr running averages of daily temperature suggested a time lag that increased with depth. A sliding cross-correlation analysis was used to find the average time lag from each depth to the next (taken to be the time lag that maximizes *r*). The surface temperature at time t_0 was correlated successively with temperature at 10 m, from time t_{-10} to t_{400}, and likewise with 10 m vs. 20 m, 20 m vs. 30 m, etc.

Using the interpolated temperature profiles together with the bathymetric curve for the lake, we calculated three measures of stability: Schmidt Stability, Birge Work and Total Work. Schmidt stability (S) is a measure of the work required to mix a thermally-stratified lake to an isothermal state without loss or gain of heat. The Birge work, (Total work minus S) or the "work of the wind", is the external energy, (both mechanical and non-mechanical) required to produce a given thermal stratification in a lake. Both can be calculated from the vertical density profile and lake bathymetry (Hutchinson, 1957; Idso, 1973; Wetzel, 2001) The Schmidt, Birge, and Total Work were seasonally-decomposed, and averaged on an annual basis for trend analysis.

2.4. TIME TREND ANALYSIS

Testing the significance of time trends in climatic and hydrologic data is usually complicated by the presence of autocorrelation in the data (von Storch, 1999). For air temperature and long-wave radiation, we calculated T_0, the "effective time between independent samples" from the autocorrelations (Trenberth, 1984), and pruned the data, discarding all but every T_0th value. T_0 for maximum and minimum air temperature was 20 days; for downward long-wave radiation, it was 4 days. We then used ordinary least squares regression to calculate the slopes of the time trends and test whether or not they differed from 0.

The record of the lake's thermal structure, however, has considerably more autocorrelation than the meteorological variables, in part because of the lake's large thermal inertia, and in part because the daily values at each depth were interpolated from data at weekly to monthly intervals. To test the significance of the upward trend in lake temperature, total heat, and Schmidt, Birge and Total Work, we first calculated the annual average values, and used "Trend Free Prewhitening" (TFPW) (Yue et al., 2002) to remove the effect of autocorrelation at lags 1 and 2. We then tested for trend significance with a Mann-Kendall test (Helsel and Hirsch, 1992).

2.5. PRINCIPAL COMPONENTS ANALYSIS AND MULTIPLE REGRESSION

In order to explore relationships between lake temperature and driving climatic variables, we used covariance-based Principal Components Analysis (PCA) together with stepwise multiple regression (in S Plus 2000). Dependent variables were seasonally-decomposed daily lake surface temperature and monthly and annual averages of seasonally-decomposed volume-weighted mean lake temperature. Explanatory variables were the seasonally-decomposed meteorological variables. The variables used in interaction terms were centered by subtracting the seasonal mean in order to reduce colinearity with the primary variables.

The annual cycle of average lake temperature does not coincide with the driving climatic variables, but lags several days to weeks behind. In order to estimate these lag times for daily surface temperature, we used a sliding correlation, and found the lag time that maximized r. For the mean monthly analysis and annual analysis, we calculated the average, for each day in the year, of mean lake temperature, maximum and minimum daily air temperature, shortwave radiation, and longwave radiation. Each of these variables, together with the corresponding daily average wind speed, was then shifted forward prior to calculating monthly and annual averages, so that the timing of annual maxima approximately coincided. Table I shows the lags used for surface temperature and average lake temperature for the different explanatory variables.

Arhonditsis et al. (2004) showed that the relationships between lake temperature and climatic drivers may be different during lake cooling than during lake warming. A preliminary analysis confirmed this difference for Lake Tahoe. Rather than separating the data into two phases, we included two continuous seasonal variables: 1) cos(day), with cos (day) $= 1$ on September 7 (on average, the lake's warmest day), and -1 on March 7, and 2) slope of the cos(day) curve, or $-\sin(\text{day})$. Values of the latter are <0 during the average cooling and >0 during the average warming phase.

TABLE I

Time lags of daily surface and volume-weighted average lake temperature behind explanatory meteorological variables. The latter were shifted forward by these amounts prior to applying the PCA and multiple regression

	Ave. lag of lake temperature behind meteorological variables (d)	
Explanatory Variable	Daily surface temp.	Vol.-ave. mean daily lake temperature
Max. daily air temp.	21	45
Min. daily air temp.	21	50
Short wave radiation	53	57
Long wave radiation	24	35

The explanatory variables tested included maximum and minimum daily air temperature, incoming solar and downward long-wave radiation, average daily wind speed, cos(day) and -sin(day), and the ENSO and PDO indices, along with interactions between the primary variables. At the daily, monthly and annual time scales, some pairs of the potential explanatory variables are correlated, especially the ENSO and PDO indices, and the daily maximum and minimum air temperature. The PCA provided a way around this problem for the mean monthly and mean annual data sets. For the daily lake surface temperature, however, a step-wise regression without the PCA gave somewhat better results than PCA with regression. To avoid the colinearity problem, we used average daily air temperature instead of maximum and minimum, and broke the data into two sets, one with ENSO index, and the other with PDO index.

2.6. THE LAKE TEMPERATURE MODEL

In order to quantify the sensitivity of the lake's thermal regime to the meteorological variables that are statistically related to measured changes in lake temperature, we set up and ran a one-dimensional, process-based, deterministic lake simulation model, known as the Dynamic Lake Model (DLM) (Hamilton and Schladow, 1997; McCord and Schladow, 1998). The equations that characterize the physical processes of the model are given by Imberger and Patterson (1990). Under the 1-dimensionality assumption, the first-order balances of mass, momentum and energy are controlled only by the vertical variations in each property. The individual processes that contribute to transport and mixing are parameterized and coupled sequentially to predict the vertical density stratification of the lake as a function of time. The model is based on a Lagrangian layer scheme in which the lake is modeled by a series of horizontal layers of uniform properties. The layer positions change in response to inflow and outflow, and layer thickness changes as the layers are moved vertically to accommodate volume changes.

The model requires lake bathymetry and initial conditions in the form of vertical profiles for temperature and salinity in the water column. Lake bathymetry is input as a table of elevation above the lake bottom and corresponding surface area and cumulative volume. Daily total inflow volumes and average daily concentrations of temperature and salinity must be given with the inflow data. Daily total outflow volumes from specified heights above the lake bottom must also be given. The required daily meteorological data for the DLM include total solar radiation, long-wave radiation, average air temperature, average vapor pressure, average wind speed, and total rainfall. The MM5 data were used for all meteorological input variables.

The DLM was previously calibrated and verified for Lake Tahoe, for a 2-yr period (Perez-Losada, 2001). In this exercise, the only adjustment to model parameters was a reduction in average daily wind speed of 38 percent. This was found to improve the fit of the model, and is consistent with statistical comparison of the 2-yr record of wind at Tahoe City with the MM5 wind.

3. Results

3.1. TIME TRENDS

The daily values of volume-weighted average lake temperature, with the seasonal cycle removed, are shown in Figure 2. Based on the Mann-Kendall test with annual means, the upward trend is highly significant ($p < 5 \times 10^{-5}$). The mean rate of temperature increase, Dec. 1969 to Oct. 2002 is $0.015 \pm 3 \times 10^{-4}$ °C yr^{-1}. Over the 33 years of record, this would amount to an increase of 0.49 °C. As with virtually all climatic time series, however, the lake temperature does not rise at a constant rate, but shows periods of cooling as well as very rapid rise. The difference in average annual lake temperature between 1970 and 2002 is 0.22 °C, but the difference between 1975 and 1992 is 0.87 °C. A linear time series model is thus a relatively crude tool, but allows us to examine the average trend, as well as some short-term anomalies (residuals) and their relationship to climatic events.

The upward trend in annual mean total heat is also highly significant ($p < 5 \times 10^{-5}$) and results in a mean rate of increase in heat storage of 22.3 M Jm^{-2}yr^{-1}, or 0.71 ± 0.02 W m^{-2}. A comparison of the warming rate of the lake with measured geothermal heat flux to Lake Tahoe of 0.068 W m^{-2} (Henyey and Lee, 1976) rules out the latter as a possible explanation of the warming trend. For that we look to the climatic variables.

The temperature at 400 m shows a clear upward trend over the 33 yr period of record (Figure 3a). Vertical lines on the Figure 3a indicate apparent mixing events, based on the nitrate and temperature gradients. No running average (RA) is necessary to smooth the curve, since the short-term (annual) temperature

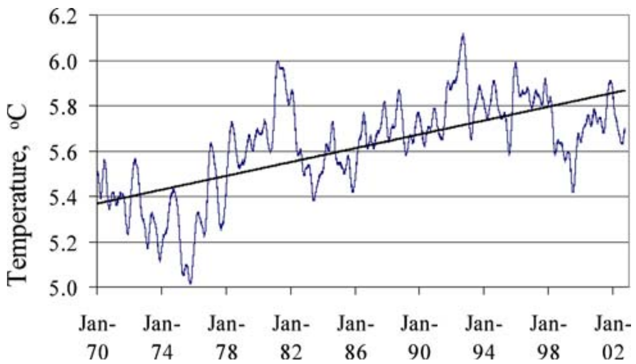

Figure 2. Daily volume-averaged mean lake temperature, after removal of the seasonal trend.

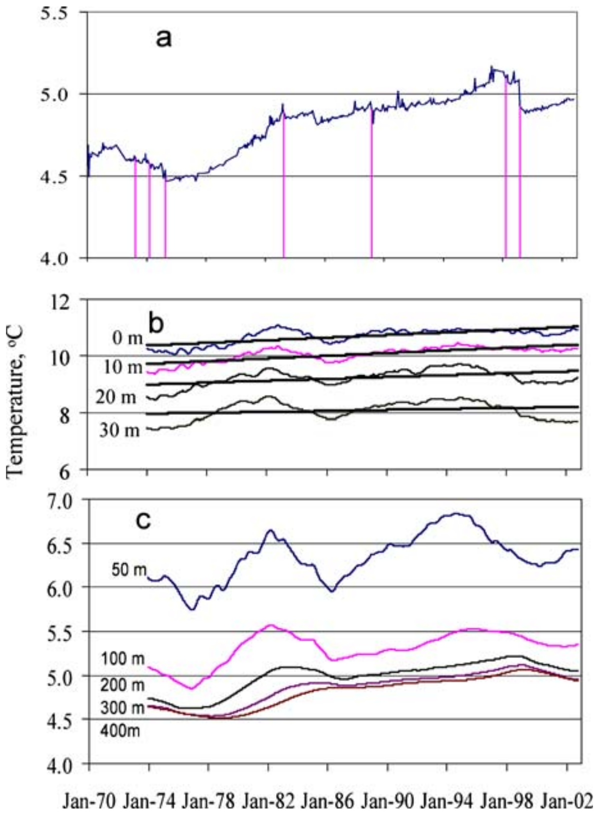

Figure 3. Temperature records for Lake Tahoe. a: Temperature at 380–420, showing apparent mixing events. The data have not been smoothed or seasonally-decomposed. b: 4-yr running average (RA) of interpolated daily temperature at depths of 0, 10, 20 and 30 m. c: 4-yr RA of interpolated daily temperature at depths of 50, 100, 200, 300 and 400 m.

fluctuations and "noise" at the surface are filtered out by the lake's thermal inertia.

When the temperature record at shallower depths is smoothed with a running average, the upward trend in temperature at all depths is apparent. Figures 3b and 3c show the 4-yr RA temperature (from interpolated daily values) at the 9 depths analyzed. Note that the curves shift forward in time and become smoother as depth increases.

Figure 4 shows the lake temperature profiles at dates close to the time of apparent mixing to at least 400 m depth that are indicated in Figure 3a. The profiles generally, but not uniformly, shift to the right over time.

An interesting feature of these time trends is that the warming rate varies with depth (Table II). The warming rate is highest at 0 and 10 m, and decreases at depths of 20 and 30 m, but increases again at 50 m. The strength of the relationship between

TABLE II
Regression results of time trends (in 4-yr running averages) at 9 depths, and time lag between depths. The time lag in temperature from one depth to the next was determined by sliding cross-correlation of daily values

Depth (m)	R^2	Slope (10^{-5} °C d^{-1})	Temperature (Time lag d)
0	0.50	6.33	
			7
10	0.59	6.55	
			9
20	0.22	4.56	
			9
30	0.04	2.32	
			6
50	0.33	5.06	
			32
100	0.37	3.69	
			85
200	0.70	4.83	
			202
300	0.83	5.36	
			177
400	0.88	5.44	

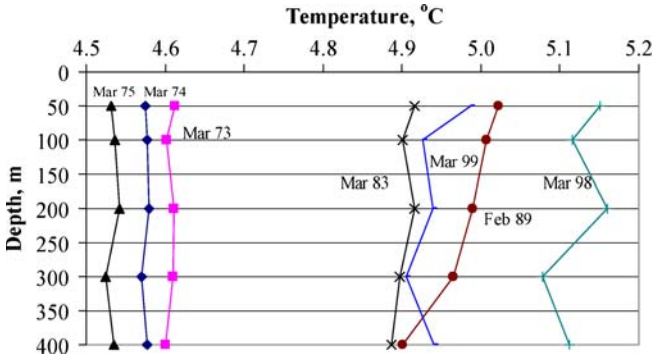

Figure 4. Temperature profiles in Lake Tahoe on or near dates of apparent mixing to depths >400 m.

temperature and time follows a similar pattern, with the highest R^2 values at 0, 10, 300 and 400 m.

Table II also shows the average time lag from each depth to the next, based on the results of the sliding cross-correlations of the unaveraged daily values. The total

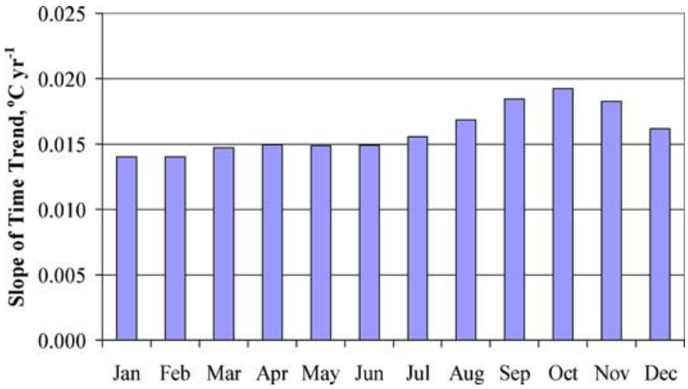

Figure 5. Slopes of the trends in average monthly temperature by month, 1970–2001.

time lag from the surface to 400 m amounts to 1.4 yrs. In other words, a climatic event at the surface affects the temperature at 400 m, on average, 1.4 yrs later.

The warming trend varies slightly by season, as well as with depth. Figure 5 shows the slopes of the time trends of monthly average lake temperature, 1970–2001. The warming trend is highest in October, then declines through late fall and winter, and increases slowly until August, then more rapidly until October.

The upward trend in lake temperature is modifying the thermal structure of the lake, and increasing its resistance to stratification and remixing. The seasonally-detrended Schmidt Stability, Birge Work and Total Work are shown in Figure 6. The upward trends in the annual averages are all significant, with $p < .06$, 4.9×10^{-7} and 7.9×10^{-4}, respectively. Figure 7 is a plot of the depth of the thermocline (defined here as the depth of the maximum vertical temperature gradient) in October, 1967–2003. The decline in depth with time is highly significant ($p < .001$).

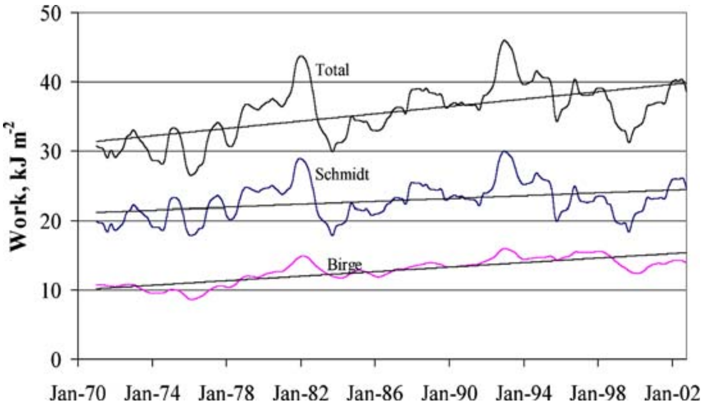

Figure 6. 1-yr RA of Total Work, Schmidt Stability and Birge Work in Lake Tahoe, calculated from interpolated daily temperature and hypsometric curve for the lake. Values were seasonally-decomposed prior to smoothing with the RA.

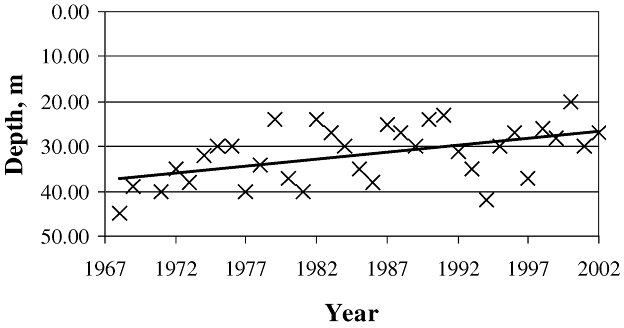

Figure 7. Maximum October thermocline depth, 1967–2002, defined as the depth of the maximum vertical temperature gradient below 10 m.

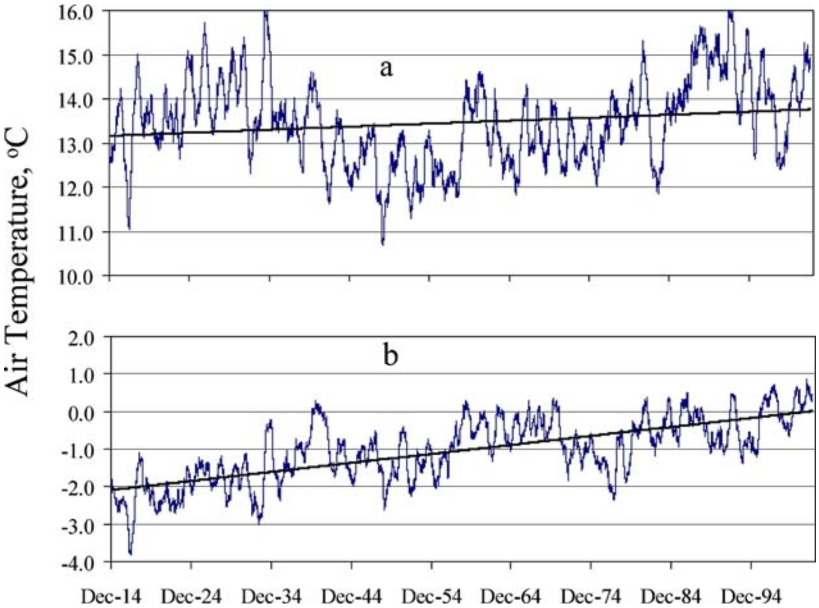

Figure 8. 1-yr running average of seasonally-decomposed daily air temperature at Tahoe City, from record of 1914–2002. a: Maximum daily. b: Minimum daily.

The trends in air temperature are somewhat dependent on the time period considered. Between 1914 and 2002, the upward trend in minimum daily temperature is highly significant ($p < 3 \times 10^{-12}$), but the upward trend in maximum daily temperature is not (p <0.19) (Figure 8a and 8b). Between 1969 and 2002, however, both maximum and minimum daily air temperature show significant upward trends ($p < 0.058$ and 0.016, respectively).

Figure 9 shows the seasonally-decomposed direct beam short-wave and downward long-wave radiation (from the MM5), 1970–2000, smoothed with a 90-day running average. There is a slight but highly significant upward trend in

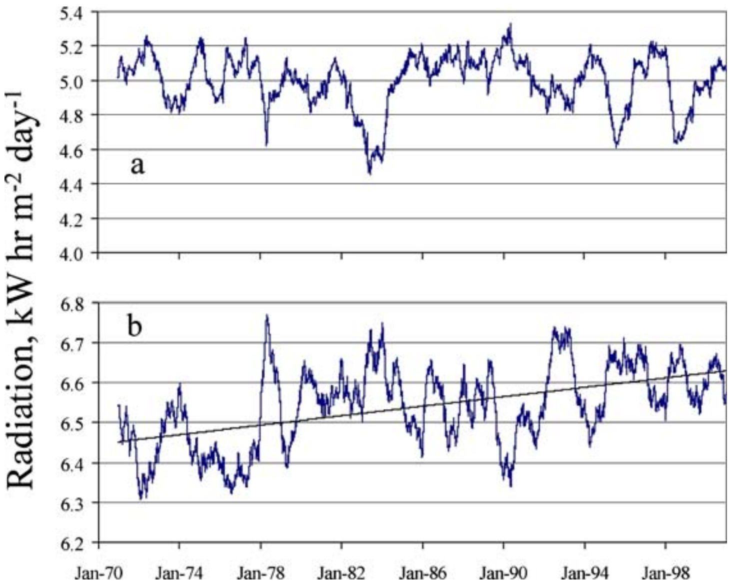

Figure 9. Solar radiation (a) and downward longwave radiation (b) at Lake Tahoe, 1970–2000, seasonally-decomposed and smoothed with a 1-yr RA running average. Data are from the National Center for Environmental Prediction (NCEP) data set, downscaled to a 3 km-2 grid scale by 5th generation Mesoscale Model (MM5) of the National Center for Atmospheric Research (NCAR).

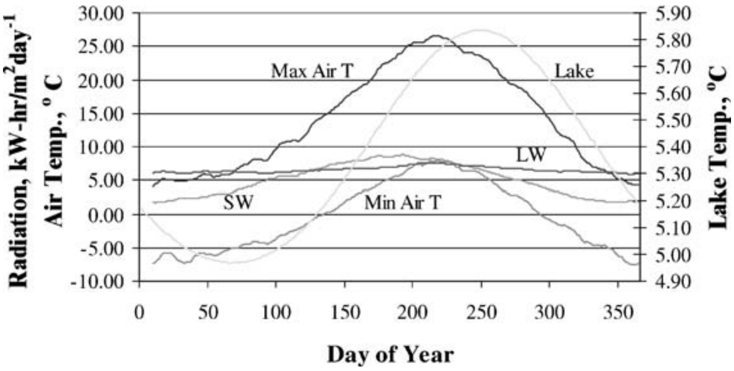

Figure 10. Average lake temperature, air temperature and radiation, by day of the year.

long-wave radiation ($p < 4.6 \times 10^{-6}$) but a very slight downward trend for short-wave radiation.

The average lake and air temperatures, shortwave and long-wave radiation, averaged by day of the year are shown in Figure 10. The averaged meteorological (met) variables have been smoothed with a 10-day running average. The average lag time of lake temperature behind the met variables was determined from this plot, and used to shift the met variables forward for use in the PCA and regression analysis of monthly and annual average lake temperature.

3.2. MULTIPLE REGRESSION

Table III shows the results of the efforts to relate daily surface temperature and average monthly and annual volume-weighted lake temperature to meteorological variables. At the daily time scale, the regressions with the two data sets explained only 17 and 19 percent of the variance in lake surface temperature ($p < 10^{-6}$). Average air temperature, short wave radiation, and the ENSO and PDO indices all entered the equation with positive coefficients, whereas wind (by itself and in interaction with air temperature and long-wave radiation) was associated with cooler temperatures. Not surprisingly, cos(day) (positive in summer, negative in winter) interacts positively with air temperature and radiation.

At the monthly time scale, the PCA with regression does a little better, with $R^2 = 0.34$ ($p < 10^{-6}$). Positive explanatory variables included maximum and minimum air temperature, short wave radiation, the ENSO and PDO indices, whereas wind and its interaction with air temperature and short wave radiation were associated with cooler temperatures. With annual average values, $R^2 = 0.74$ ($p < 10^{-6}$); the positive coefficients include maximum and minimum air temperature, wind, the ENSO and PDO indices, and interactions of wind with minimum daily temperature and short wave radiation. The coefficients for short wave radiation and maximum temperature $\times$ wind, however, were negative.

3.3. LAKE TEMPERATURE MODEL

The temperature model, after adjustment of the daily wind values, does a good job of predicting the measured average daily lake temperature, with $R^2 = 0.87$, and S.E. $= 0.18\,^{\circ}$C. With the seasonal cycle removed from both the average daily lake temperature data and the model results, $R^2 = 0.39$, and S.E. $= 0.17\,^{\circ}$C.

Figure 11 shows the modeled and measured time trends in volume-weighted average lake temperature, seasonally-decomposed and smoothed with a 2-yr RA. Removing the trend in downward long-wave radiation in the input data (but not the air temperature trend) slightly reduces the modeled rate of temperature increase. Removing the air temperature trend (but not the long-wave radiation trend) reduces the trend somewhat more. Removing both trends results in a slight cooling in the lake temperature. The fitted slope of the time trends for these different scenarios are compared in Table IV with the slope of the measured temperature trend over the same time period.

In Figure 12 we compare the modeled and measured mixing depth, by year. The input data used were the un-detrended MM5 data, and the same data with both the air and long-wave radiation trends removed. The DLM successfully predicts both the state (fully mixed or not mixed) and the maximum annual mixing depth (MAMD). In nine years of the series, there is very close agreement between the simulated and measured MAMD. Only two years (1982 and 1989) are clearly off.

TABLE III
Results of step-wise multiple regression of daily lake surface temperature, and PCA followed by step-wise multiple regression of average monthly and annual lake temperature with meteorological variables

	Lake surface temperature		Average lake temperature	
	Daily, set 1	Daily, set 2	Ave. Monthly	Ave. Annual
R^2	*0.171*	*0.193*	*0.336*	*0.744*
Variable				
Max air t	na	na	+	+
Min air t	na	na	+	+
Ave air t	+	+	na	na
SW rad	+	+	+	−
LW rad	0	na	0	0
Wind	−	−	−	+
ENSO Index	+	na	+	+
PDO Index	na	+	+	+
Maxt × wind	na	na	−	−
Mint × wind	na	na	−	+
Aveair × wind	−	−	na	na
SW rad × wind	+	+	−	+
LW rad × wind	−	−	0	0
Cosday	0	na	+	na
d(cosday)	0	na	0	na
Cosday × SW rad	+	na	−	na
Cosday × LW rad	+	na	0	na
Cosday × ave air t	+	na	na	na
Cosday × wind	na	na	+	na
d(cosday × SW rad	0	na	−	na
d(cosday) × LW rad	0	na	0	na
d(cosday) × wind	na	na	−	na
d(cosday) × aveair t	−	na	na	na

The principal component loadings have been condensed by multiplying by the appropriate regression coefficient, and summing across components. Lake temperature, maximum and minimum daily air temperature and radiation and associated wind were lagged and seasonally-detrended. Each variable with a + or − sign makes a highly significant contribution to R^2. The ± signs indicate the sign of the coefficient for each variable. A "0" indicates a tested variable that did not make a significant contribution, and "na" indicates a variable was not included in the suite of explanatory variables that were tested. $P < 0.05$ for all variables indicated with a "+" or "−".

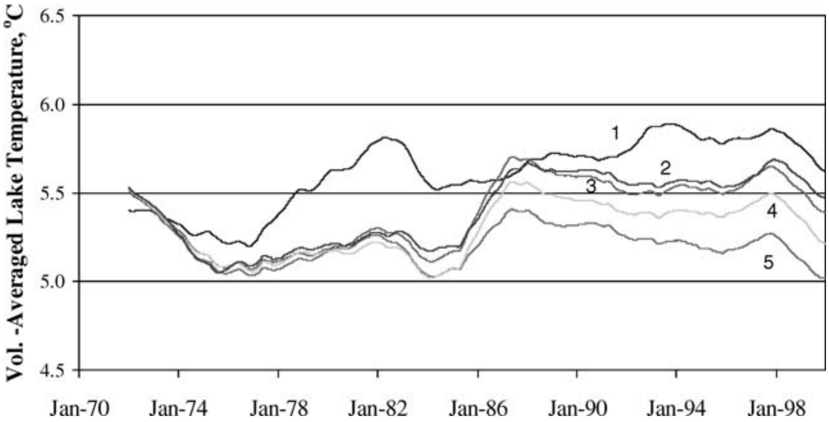

Figure 11. Results of the temperature model, compared with the measured average lake temperature (1). The curves indicate the modeled lake temperature with no detrending (2), only long-wave radiation detrended (3), only air temperature detrended (4), and both air and long-wave radiation detrended (5).

The discrepancies may be due to misinterpretation of the MAMD from the nitricline data, especially in 1982.

4. Discussion

Lake Tahoe is the largest entire lake in North America for which a warming trend has been documented; it joins a growing list of lakes around the globe for which a long-term warming trend has been shown, and related to climate change (see Table V). Perhaps coincidentally, the warming rate for Lake Tahoe (0.015 °C yr^{-1}

TABLE IV

30-yr change in average volume-weighted temperature of Lake Tahoe, with and without long-term upward trends in air temperature and long-wave radiation

Input assumption	30-yr Δt (°C)
Both detrended	−0.08
Air temp. only detrended	0.17
LW radiation only detrended	0.38
No detrending	0.44
Measured	0.52

Input data are from the MM5 results; rates of change are from the fitted slopes.

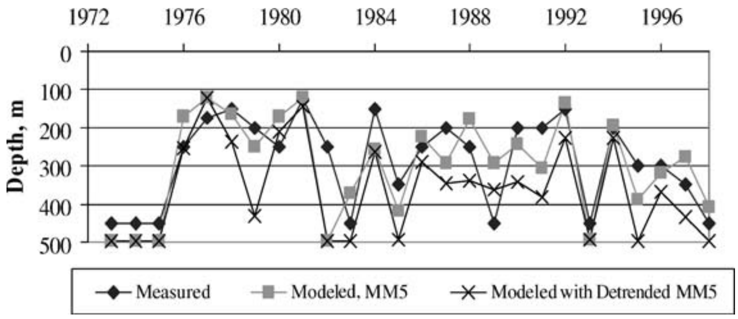

Figure 12. Depth of mixing in Lake Tahoe, measured by nitrate and temperature profiles, modeled with the MM5 data, and modeled with air temperature and long-wave radiation trends removed from MM5 data.

or 0.71 W m^{-2}) almost coincides with a recent estimate of the globally-averaged rate of atmospheric warming of 0.017 °C yr^{-1} (Jones and Moberg, 2001). It is somewhat greater than the warming rate (1948–1998) of the upper 3 km of the world's oceans of 0.42 W m^{-2} (per unit area of the Earth's ocean surface) (Levitus et al., 2000), and slightly less than the global imbalance in the Earth's radiation budget (0.85 W m^{-2}) recently reported by Hansen et al. (2005).

It is important to consider the warming trends in the Tahoe basin (both lake and air temperature) in a regional as well as global context. Dettinger and Cayan (1995) found an upward trend in winter temperature in the Sierra Nevada (1948–1991), and related a trend toward earlier spring runoff to the temperature trend. In a subsequent modeling study of climate change in the northern Sierra Nevada, Dettinger et al. (2003) found that historical simulations showed significant warming beginning about 1975, resulting in a shift toward earlier snowmelt and streamflow peaks. This shift is wide-spread across western North America (Stewart et al., 2005).

At Tahoe City, the 1914–2002 air temperature record shows a strong upward trend in minimum but not maximum daily temperature, and the MM5 downward long-wave radiation (1970–2000) also shows a significant upward trend. Both of these observations are consistent with a greenhouse gas-induced suppression of night-time longwave re-radiation, and are in line with findings from long-term temperature records elsewhere in the world (Livingstone, 2003; Kukla and Karl, 1993).

Consistent with Dettinger et al. (2003), the temperature record in Lake Tahoe shows a long upward run beginning in 1975 and continuing through 2002, with short cooling periods in 82–83, 92–93 and 97–99. The 1982–83 anomaly, shown in Figures 2, 8 and 9, may be due to the eruption of El Chichón (Chiapas, Mexico) in the spring of 1982. The sulfate aerosols from that eruption reduced solar radiation throughout the northern hemisphere, and had a significant effect on air temperatures (Kerr, 1982). 1983 was also a strong El Niño (ENSO) year, but the

TABLE V
Warming trends in lakes around the world

Lake	Location	Period	Warming Rate, °C yr^{-1}	Basis	Reference
Lake Tahoe	Calif.-Nev.	1970–2002	0.015	Vol.-wtd ave.	This study
Lake Washington	Seattle, WA	1964–98	0.026	Vol.-wtd ave.	Arhonditsis et al. (2004)
Lake 239	NW Ontario	1964–98	0.108	Depth- ave.	Schindler et al. (1996)
Lake Maggiore	Italy	1963–98	0.03	Vol-wtd.ave.	Ambrosetti and Barbanti (1999)
Lake Zurich	Switzerland	1947–1998	0.016	Vol.-wtd. ave.	Livingstone (2003)
9 lakes	Signy Isl., Antarctica	1980–95	0.06	"Mean winter lake water temperature"	Quayle et al. (2002)
Lake Tanganyika	E. Africa	1913–75	.0042	Depth-ave.	Verberg et al. (2003)
		1975–2000	.0039		
Lake Malawi, > 300 m depth	E. Africa	1939–99	0.01	Vol.-wtd. ave.	Vollmer et al. (2005)

TABLE VI
Possible climatic anomalies after the eruptions of El Chichón (1982) and Mt. Pinatubo (1991)

Variable	Year 1981	1982	1983	1992	1993
Lake temp.	2.56	0.60	−0.70	1.88	0.46
Max. daily air temp	1.37	−1.76	−1.59	1.80	−0.60
Min. daily air temp	1.91	−0.87	0.75	0.73	1.65
SW radiation	−0.10	−1.57	−2.98	−0.62	0.23
LW radiation	1.46	−0.14	2.40	1.29	−0.48

Variables are shown as the deviations from the trend line of annual averages, in standard error units. The two-year drop in lake temperature from 1981–83 was the largest in the 1970–2002 period of record.

positive regression coefficients for the ENSO index (Table III) indicate that it is more often associated with warming rather than cooling of the lake. There was some argument at the time, however, that the ENSO event itself was triggered or at least strengthened by the eruption (Kerr, 1983). Table VI shows the deviations from the trend line (in SE units) of annual averages for lake temperature, maximum and minimum daily air temperature, and radiation. The drop in lake temperature from 1981–1983 was the largest 2-year drop in the period of record. There also seems to be a delayed effect of the eruption of Mt. Pinatubo in the Philippines on both lake and air temperature; air temperature records (Hansen et al., 1996; Easterling et al., 1997) and lake mixing depths (King et al., 1997) elsewhere show a delayed "Pinatubo effect".

The upward trend in lake temperature varies only slightly by month (Figure 5), with October showing the highest rate of warming (0.019 °C yr^{-1}), and January and February the lowest (0.014 deg C yr^{-1}). This contrasts sharply with lake Washington (Arhonditsis et al., 2004), where the seasonal differences were greater, with April showing the highest slope of the temperature trend (0.047 °C yr^{-1}) and December the lowest (.003 °C yr^{-1}). The difference is probably due to differences in climate (montane vs. maritime) and lake volume (157 km^3 vs. 2.9 km^3).

The PCA and stepwise multiple regression of lake temperature vs. meteorological variables shows the importance of air temperature, at the daily, monthly and annual time scales. Short wave radiation was positively related to water temperature at the daily and monthly time scales, but with the annual average data set, the coefficient was negative. This may be a result of the long-term upward trend in lake temperature vs. the long-term slight downward trend in short wave radiation. More puzzling is the lack of significance of long wave radiation, which the model shows is a significant factor in the long-term warming of the lake. The long wave data, however, show a lower variance than the other meteorological variables; the coefficients of variation of the seasonally-decomposed air temperature and short wave radiation are almost 3 times that of the long wave radiation. Apparently the lake temperature is not sensitive to the relatively small short-term variation in long wave radiation, but is responding to its long-term upward trend.

The pattern for wind is the opposite of that of short wave radiation, with negative coefficients for daily and monthly time scales, but a positive coefficient for annual averages. Seasonal differences may come into play here. The coefficient for the cosday $\times$ wind interaction is positive at the monthly time scale, suggesting wind is associated with warming of the lake during the summer and cooling it during the winter.

The ENSO and PDO indices show a consistently positive relationship with lake temperature, at all time scales. In other lakes of North America, temperature as well as ecological variables have been linked to the ENSO index (MEI) and the PDO index. In Lake Washington, Arhonditsis et al. (2004) found a strong correlation between PDO and lake temperature for both the warming (March-October) and the cooling (November-February) phases. MEI was also positively correlated with the temperature of Lake Washington for both phases, but less so than PDO. At Castle Lake (area $= 0.2$ km^2) in the mountains of northern California, there is a complex relationship between ENSO events and lake warming, with an abnormally warm lake in some ENSO years, and an abnormally cool lake in others, depending largely on snow accumulation and time of ice-out (Strub et al., 1985).

In 1976–1977, the PDO shifted from the cool (negative) to the warm (positive) phase (Mantua, 1997). The long upward run in lake temperature at Tahoe roughly coincided with this phase shift. In 1989–91, the PDO temporarily reversed back to the cool phase, but this reversal was not accompanied by any remarkable cooling of the lake. In 1999 it again shifted to the cool phase, and remained in that phase until at least 2002 (Stewart, et al. 2005). That more recent phase shift is associated with two deep mixing events, and a slight two-year cooling trend before the lake temperature resumed its upward climb. In summary, the PDO, ENSO and occasional volcanic eruptions impose short-term fluctuations on the long-term trend that seems to be driven by rising air temperatures and (to a lesser extent) downward long-wave radiation.

Perhaps the greatest significance of the upward trend in lake temperature at Tahoe is its impact on lake stability and resistance to mixing. From 1970 through 2002, the Schmidt Stability increased by 17 percent, the Birge Work by 49 percent, and the Total Work by 27 percent. The increasing temperature is increasing the lake's thermal stability for two reasons. First, the lake is warming faster at 0 and 10 m than at greater depths (Table II). Second, the rate of change of water density with temperature is non-linear above 4 °C, so that (other things being equal) a warm lake is more stable than a cold lake, even without a time trend in temperature. Note in Figure 3 that the lake mixed below 400 m 3 times during the cooling period of the early 1970s, but only 4 times in the subsequent 25 years.

The detrending experiments with the DLM (Figure 12) showed that without the trends in air temperature and downward longwave radiation, the maximum annual mixing depth (MAMD) would consistently be greater, and the lake would be less stable. Moreover, without the time trends in the two driving variables, the lake would have mixed completely in 5 additional years between 1973 and 1998 (1979, 1983, 1985, 1995, and 1998).

The increasing stability and resistance to mixing may explain the anomalous time trend of temperature at 30 m depth. At that depth, there is scarcely any upward time trend of temperature, whereas the trends at 0 and 10 m, and 50–400 m are clear-cut. Annual maximum temperature at 30 m (but not other depths) actually shows a decline between 1992 and 2002.

There is a clear trend ($p < 0.001$, by Mann-Kendall test with TFPW) toward decreasing maximum thermocline depth in October, but not in August or September. Early fall mixing is reaching a depth of 30 m less often now than in the 1970s, so that the temperature regime at 30 m is increasingly more characteristic of the deep water than of the epilimnion or thermocline.

To explore the causes of this "epilimnial compression", we ran a step-wise multiple regression of depth of the October thermocline with the Schmidt stabilities, average monthly wind, and average monthly Secchi depths, for August, September and October. Only September Secchi depth ($p < .08$) and September wind ($p < .14$) were even slightly related to the thermocline depth. Although October thermocline depth is weakly related to September wind, there is no significant time trend ($p < 0.38$) in September wind, so a long-term decrease in September wind cannot be responsible for the decreasing thermocline depth.

Two mechanisms could operate to cause an inverse relationship between transparency and thermocline depth. First, the decreasing transparency in the lake may decrease the depth of the layer in which solar radiation input is concentrated. Studies of the relationship between water clarity, lake size and epilimnion depth in Canadian Shield lakes found that epilimnion depth is related to water clarity, but its importance declines with lake size (Mazumder and Taylor, 1994; Fee et al., 1996). King et al. (1997) suggested that in large lakes there would be little short-term response of thermal structure to changes in water clarity, but that there could be a significant response on a decadal time scale.

Second, the decreased mixing could help retain small particles in the epilimnion, where they have maximum impact on lake clarity. More physical modeling may help to determine whether such a positive feedback mechanism is possible. The first hypothesis could be tested by running the model with and without the observed trend in transparency. To test the second hypothesis, however, would require good data on the size distribution of particles $<20\ \mu$m in stream sediment loads, which are not yet available.

The changes in Lake Tahoe's thermal structure reported here are consistent with findings for other lakes around the world. At Lake Mendota in Wisconsin (Robertson and Ragotzkie, 1990) statistical analysis and modeling showed that increasing air temperatures cause an increase in resistance to mixing and a decrease in depth of the late summer to early fall thermocline. Statistical analysis of South Bay (Lake Huron) suggested that climate warming is likely to lead to earlier onset of stratification (which we did not observe at Tahoe), as well as larger temperature differences in the water column, which would increase the resistance to mixing (King et al., 1997). Over a 52-yr period of record, warming of Lake Zurich has caused a 68 percent increase in Schmidt stability during winter and a 15 percent increase in autumn (Livingstone, 2003). Application of a one-dimensional temperature model to Lake Michigan showed that climate warming will decrease summer thermocline depth, increase resistance to mixing, and could even lead to the creation of a permanent deep-water thermocline (McCormick, 1990).

4.1. ECOLOGICAL IMPLICATIONS

From 1969 to 2002, the volume-averaged rate of warming in Lake Tahoe amounted to 0.015 °C yr^{-1}. The most significant effects on the lake ecosystem will most likely be associated with the increased thermal stability and resistance to mixing.

First, fine (<20 μm) inorganic sediment has been shown to play an important role in reducing the clarity of the lake. This impact is greatest in years following heavy stream runoff, and is prolonged by an absence of deep-water mixing events (Jassby, 1999). Following mixing, the fine sediment is dispersed throughout the volume of the lake, and clarity is increased. Reduced mixing may thus prolong the periods of reduced clarity that follow heavy runoff. To complicate matters, the shift toward earlier snowmelt (Stewart et al., 2005) may interact with the changing thermal structure of the lake to change the "insertion depth", that is, the depth at which the density of stream inflow and lake water are equal. A coupled watershed-lake model is needed to fully analyze the effects of climate change on fine sediment in the lake.

Second, the increased stability and decreased thermocline depth may affect the feeding behavior and population structure of zooplankton. During the summer, the thermocline provides a thermal refugium for some zooplankton. When surface temperatures reach 15 °C, the thermocline becomes an effective barrier that protects cladocerans and copepods from predation by an introduced mysid shrimp (Richards et al., 1991). A greater thermal gradient associated with warming of the lake might increase the strength of this barrier. The partial recovery of the populations of the cladocerans *Bosmina* and *Daphnia*, which were devastated by the 1963–1965 introduction of *Mysis relicta* (Richards et al., 1975) coincides with the warming trend in the lake since the mid-1970s. It also coincides, however, with increasing primary productivity and changes in phytoplankton species composition, and we do yet not have the data necessary to sort out the relative importance of these factors. The potential impact of climate change on the lake's biota remains a fertile area for future research.

Third, the increased stability may modify the biogeochemical cycling of nitrogen and phosphorus in the lake, reducing the regeneration of nutrients from deep water during years without deep mixing, and enhancing it during the increasingly-infrequent years of full mixing. In Lake Tahoe, deep mixing events in March are associated with increased primary productivity in May (Jassby et al., 1992). A decrease in deep mixing might thus increase the importance of external loading relative to internal loading, and shift the timing of the annual peak in primary productivity.

In meromictic Lake Tanganyika, (permanently stratified by a chemically-enhanced density gradient) warming over an 87-yr period has increased the vertical density gradient and reduced the regeneration of nutrients from deep water sufficiently to reduce primary production, shift plankton species composition, increase water clarity and reduce the depth of oxygen penetration in the upper mixed layer (Verburg et al., 2003). And in Mono Lake, a hypersaline terminal lake in the Eastern Sierra, a 6-yr period of meromixis was induced by unusually heavy runoff during the ENSO years of 1982–1983. Available nitrogen was depleted in the upper waters until the lake mixed fully in late 1988, releasing a pulse of ammonium (accompanied by sulfide and methane) that stimulated an unprecedented algal bloom and brine shrimp population increase (Jellison et al., 1993; Miller et al., 1993). The ecological changes associated with increased stability that may be expected for Lake Tahoe are no doubt very different from these two examples, but may be nonetheless significant.

For Lake Tahoe, the ultimate biogeochemical "worst case scenario" would be the interaction of increased stability with increasing primary productivity and reduction of the dissolved oxygen concentration (DO) in deep water. Long-term data on the DO conditions at the sediment-water interface in Lake Tahoe are lacking. Reduced mixing, combined with continued influx of nutrients from runoff and atmospheric deposition (Jassby et al., 1995), however, may ultimately cause hypoxia at the sediment surface in deep water, triggering a release of soluble reactive phosphorus. Then when a deep mixing event finally occurs, the released phosphorus would be dispersed into the photic zone, stimulating an unprecedented algal bloom. The time it will take to reach such a threshold will depend on the future rate of climate change as well as the success of on-going efforts to reduce the anthropogenic flux of nutrients to the lake.

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