LAKE WATER TEMPERATURE

Lake Tahoe waters are warming in response to warming air temperatures in the Sierra Nevada.

Figure 1.
Annual average water temperature

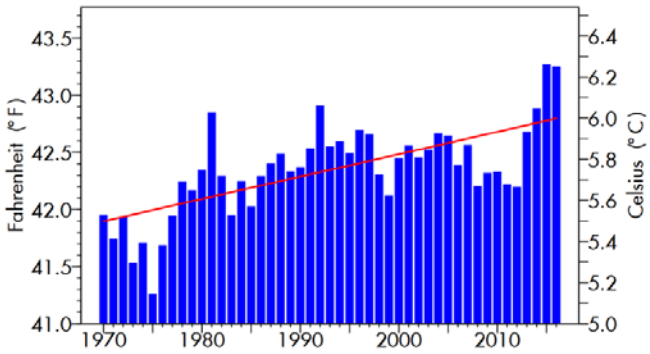
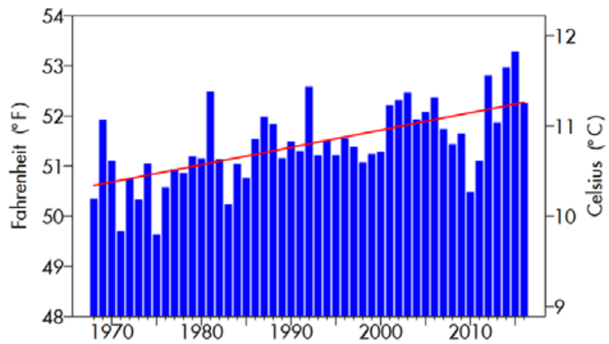


Figure 2.
Annual average surface water temperature



Source: UC Davis, 2017

What does the indicator show?

Average lake water temperatures at Lake Tahoe have increased by nearly a full degree Fahrenheit (°F) since 1970 at an average rate of 0.02°F per year (Figure 1). The lake warmed from 1970 until the 1990s, began to cool between 1997 and 2011 due to deep mixing (see below), and has since warmed again. Warming accelerated in the last four years by about 10 times faster than the long-term rate.

Surface water temperatures have also increased (Figure 2). The overall warming of the lake surface is on average almost 0.04°F per year. Temperatures fell in 2016 due to cool summertime air temperatures and a large increase in winds. In 2015, the average surface water temperature was the warmest on record.

Why is this indicator important?

Climate change is among the greatest threats to lakes (O'Reilly et al., 2015). Lakes are sensitive to climate, respond rapidly to change and integrate changes in the land areas that drain into them (catchment). Thus, they also serve as good sentinels for climate change. Aquatic habitats most vulnerable to climate effects, especially rising temperatures, are alpine lakes like Lake Tahoe that sit at high altitude and latitude.

In a warming climate, tracking changes that are detrimental to lake water quality is critically important. Even seemingly small changes in lake temperature can significantly affect key physical and biological processes (O'Reilly et al., 2015). Rising water temperatures reduce water quality by increasing thermal stability and altering mixing patterns (discussed in next section). These changes can result in the creation of niches for species that previously could not survive in the lake but could now survive if introduced, potentially disadvantaging native species that have evolved under clear, cold water conditions. Elevated water temperatures can also increase metabolic rates of organisms, from plankton to fish (UC Davis, 2017).

During the summer, Lake Tahoe waters are stratified, with warm, lighter waters at the surface, and cold, denser waters at depth. Between these layers is the "thermocline," a region in which the temperature declines rapidly with depth. Thermal stratification occurs in the warm season because of the large differences in density between the warm and cold waters. In the late fall and winter, Lake Tahoe's waters undergo "deep mixing," as surface waters cool and sink to the bottom, and upwelling brings nutrients to the surface. This mixing plays a critical role in providing nutrients to the food web and distributing oxygen throughout the lake. Without this circulation, oxygen-rich surface water does not make it to the lake bottom, depriving fish and other aquatic life of oxygen.

Credit: California Tahoe Conservancy

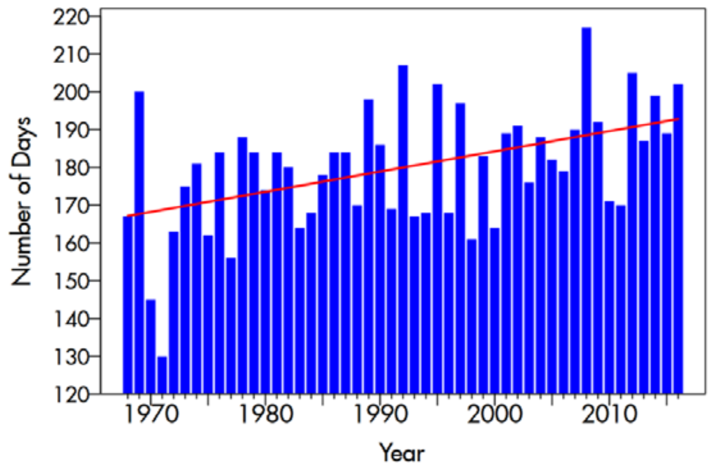
Lake Tahoe is a crystal-clear high altitude alpine lake, considered one of the jewels of the Sierra. World-renowned for its striking blue color and amazing clarity, majestic beauty, close proximity to urban areas, and opportunities for hiking, skiing, camping, boating and a host of other recreational activities, the lake draws millions of visitors to the area every year (CTC, 2017).

Lake Tahoe is 22 miles long, has a surface area of 190 square miles, and a total volume of 130 million acre feet. Its maximum depth of 1,644 feet makes it the third deepest lake in North America, and the eleventh deepest lake in the world.

Since 1968, the lake's waters have undergone deep mixing every three to four years, on average. However, Lake Tahoe has not mixed to its full depth in the past five years. Resistance to lake mixing across the thermocline increases markedly even at a temperature gradient of only a few degrees between stratified layers (Sahoo et al., 2015). Record-high water temperature in 2016 hindered the lake's deep mixing. The lake mixed to a depth of only 540 feet, one-third of its maximum depth. Scientists are predicting that in a warming climate mixing in Lake Tahoe will become less frequent — a change that will disrupt fundamental processes that support a healthy ecosystem (UC Davis, 2017).

Thermal stability determines "stratified season length," the number of days when the lake is resistant to mixing (based on the amount of energy required to mix the lake). The stratification season has been starting earlier with the early arrival of spring temperatures, and ending later as the fall season for the lake has been ending later. Figure 3 shows increasing stratified season length in Lake Tahoe over the years 1968-2016. Although there is considerable year-to-year variation, overall the stratification season has lengthened by almost 26 days. A prolonged season length can potentially impact species composition, organism abundance, and lake productivity.

Figure 3. Stratified season length



Source: UC Davis, 2017

The lack of seasonal lake mixing can cause shifts in Lake Tahoe's algal species and their distribution (UC Davis, 2017). Most algae are free-floating in the lake's turbulent environment, which prevents algae from sinking out of the sunlight. Turbulence suppression, due to stratification, causes the larger algae to sink and leaves the smallest algae at the surface with no competition for nutrients. One of the most common is *Cyclotella gordonensis*, a tiny diatom. When *Cyclotella gordonensis* is suspended in the water for extended lengths of time it scatters light and decreases the lake's clarity. As clarity decreases, greater warming of the surface water takes place, increasing stratification and the likelihood of more small algal species. This vicious cycle presents an additional climate-induced challenge. Reduced mixing may also prolong periods of reduced lake clarity that occur following years of heavy stream runoff, by causing fine particles to be retained in the upper layer of the lake (Coats et al., 2006).

Water clarity measurements have been taken continuously at Lake Tahoe since 1968 using an instrument called a Secchi disk (UC Davis, 2017). This monitoring has allowed a better understanding of how various factors, including temperature, precipitation, and nutrient and sediment inputs into the lake associated with land use and human activities are changing physical, chemical, and biological processes that affect the lake's clarity. Although lake clarity over this period has been declining overall, the rate of decline has slowed somewhat over the last decade, with notable differences between winter and summer clarity. Since 1968, winter clarity (December–March) has shown a general improvement. However, summer clarity (June–September) shows an overall decrease over time. In 2016, decreased clarity was caused by large increases in the concentration of *Cyclotella gordonensis* due to an early onset of spring and strongly stratified lake conditions.

In addition to Lake Tahoe, warming has been reported in other lakes in the western United States. Temperature data derived from satellite observations show increasing summertime surface water temperatures in a study of four lakes in Northern California (including Lake Tahoe) and two in Nevada (Schneider et al., 2009). From 1992 to 2008, these six lakes showed a significant warming trend for summer (July through September) nighttime surface temperatures, ranging from 0.05 degrees Celsius (°C) per year at Clear Lake to 0.15°C per year at Lake Almanor and Mono Lake. The lakes exhibited a fairly similar rate of change, with the mean warming rate of 0.11°C per year (± 0.03°C per year).

The scenic beauty of Lake Tahoe offers recreational and cultural opportunities. The annual tourist population of 4.5 million makes it a region of national economic significance, with estimated annual revenues of 4.7 billion dollars (Mooney and Zavaleta, 2016). A decline in the famous water clarity and ecosystem health of the lake could jeopardize future tourism.

What factors influence this indicator?

Key drivers controlling lake surface water temperature are air temperature, solar radiation, humidity, ice cover, and wind. Lake temperatures are also mediated by local factors such as lake surface area, volume, and depth. A study of lakes around the world found summer air temperature to be the single most important and consistent predictor of lake summer surface water temperature (LSSWT) (O'Reilly et al., 2015). The study reported that LSSWT is warming significantly, with a mean trend of 0.34°C per decade across 235 globally distributed lakes between 1985 and 2009. This warming water surface rate is consistent with the annual average increase in air temperatures and ocean surface temperatures over a similar time period (1979–2012).

Lake Tahoe warming trends reflect overall air temperature trends in the region (UC Davis, 2017). Lake Tahoe's accelerated warming over the last four years is of special concern, since its enormous volume should make it less vulnerable to change. Over the last 105 years, the average daily maximum air temperature at Tahoe City has risen by 1.1°C (2°F) and the nighttime minimum temperature by 2.4°C (4.3°F). A warming climate is affecting other physical changes at Lake Tahoe — including a shift from snow to rain and a shift in snowmelt timing to earlier dates — that may have significant impacts on lake ecology and water quality. For more information about meteorological trends in the Lake Tahoe area, refer to: *Tahoe: State of the Lake 2017* (UC Davis, 2017).

Technical Considerations

Data Characteristics

The University of California, Davis and its research collaborators collect the measurements used for monitoring Lake Tahoe. They have recorded water temperature measurements at two locations in Lake Tahoe since 1969:

(1) at the Index Station (about 0.3 kilometers off the California side west shore) at depth increments of 2 to 15 meters starting at the surface to a depth of about

100 meters, on an approximately weekly basis (and since 1996 at 1-meter increments to a depth of 125 meters biweekly);

(2) at the Midlake Station, the exact location of which has varied slightly over time, at nominal depths of 0, 50, 100, 200, 300 and 400 meters, on an at least monthly basis (Coats, 2006).

Strengths and Limitations of the Data

A variety of thermometers and digital thermographs have been used at the Index Station over the years. Although the sensitivity, accuracy, and calibrations of these instruments have varied over time, these data are adequate for characterizing the thermal structure of the epilimnion and thermocline. Temperatures at the Midlake Station were originally measured at 13 depths with mercury-reversing thermometers, as follows: a protected thermometer, unaffected by pressure, records the temperature at reversal depth; readings from this thermometer are corrected for glass expansion and, along with a second, unprotected thermometer affected by pressure in deep water, provide measure of the actual depth of the temperature reading (Coats et al., 2006). These instruments were accurate to 0.01^{o}C. More recently temperature is measured using a high precision thermistor that is part of a suite of instruments on a Seabird SBE-25 profiler. Accuracy of the thermistor is 0.001^{o}C. The Seabird measures at a rate of 8 times per second as it falls through the water at a velocity of 60 centimeters/sec.

Lake temperature data derived from thermal infrared satellite imagery (ATSR and MODIS), when validated against corresponding *in situ* data for Lake Tahoe, were found to agree very well over the entire range of temperatures. This, along with an additional assessment of inter-sensor bias between all ATSR sensors, indicates that accurate and stable time series of lake surface temperature can be retrieved from ATSR and MODIS satellite data.

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