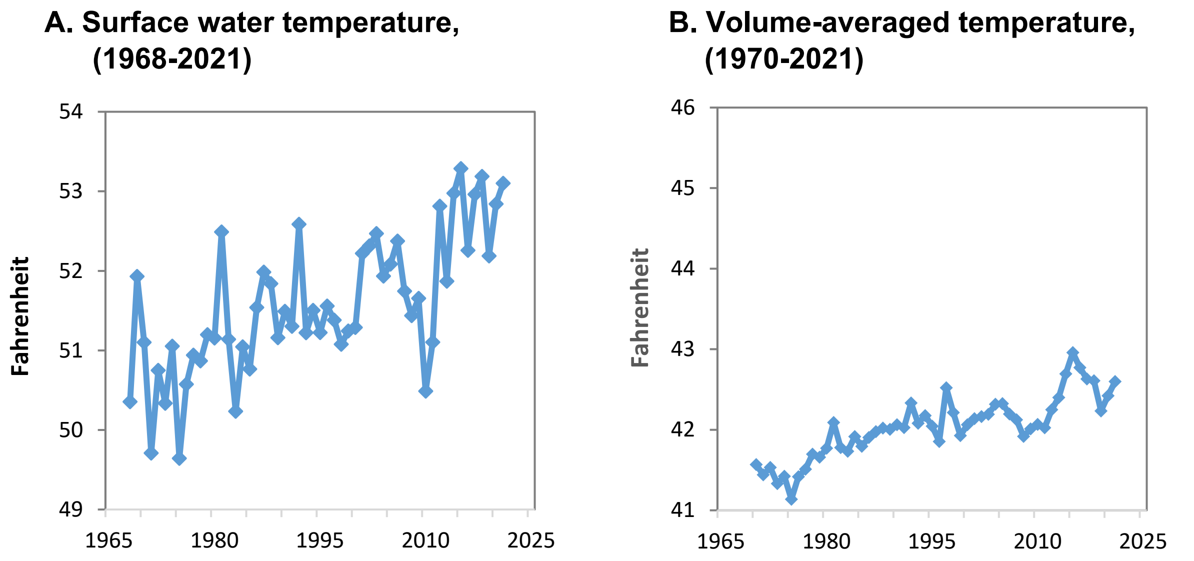
LAKE WATER TEMPERATURE

Lake Tahoe waters are warming in response to changing climate conditions in the Sierra Nevada.

Figure 1. Annual average water temperatures at Lake Tahoe



Source: UC Davis, 2022

What does the indicator show?

Annual average surface water temperatures at Lake Tahoe, which varied greatly from year to year, have increased by 1.97 degrees Fahrenheit (°F) since 1968, at a rate of 0.39°F per decade (Figure 1A). The highest average surface temperatures were recorded in seven of the last 10 years, with 2015 reporting the warmest on record (53.29°F).

Figure 1B shows annual average lake water temperatures across multiple depths (”volume-averaged”). Volume-averaged temperatures have warmed overall in the past fifty years by approximately 1.1°F, at a rate of 0.22°F per decade: a smaller increase compared to surface water temperatures (Figure 1A). After peaking in 2015, volume-averaged temperatures trended down until 2019, but showed an uptick in 2020 and 2021.

While Lake Tahoe is unique, the physical, chemical and biological forces and processes that shape it reflect those acting in most natural ecosystems. Thus, Lake Tahoe can serve as an indicator for other systems both in California and worldwide (UC Davis, 2022).

Warming has also been reported in other lakes in the western United States. Temperature data derived from satellite observations show increasing summertime surface water temperatures in a 16-year 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).

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. Lakes in mountain regions may be particularly sensitive to ongoing changes in climate in part because high-elevation ecosystems are warming at among the fastest rates found globally. Aquatic habitats most vulnerable to climate effects, especially rising temperatures, are alpine lakes like Lake Tahoe that sit at high altitude.

Even small changes in water temperature are known to affect physical and biological processes and the functioning of ecosystems in mountain lakes (Sadro et al., 2019). In the Sierra, interrelated factors such as the amount of snowpack, the timing and magnitude of snowmelt, and water temperature have important implications for growth of benthic algae and phytoplankton, primary productivity and food web dynamics. Elevated water temperatures can increase metabolic rates of organisms, from plankton to fish (UC Davis, 2022).

Rising lake water temperatures reduce water quality by increasing thermal stability (stratification) and altering lake mixing patterns (O'Reilly et al., 2015). During the summer, Lake Tahoe water forms horizontal layers with less mixing due to differing water temperatures. In the late fall and winter, surface waters cool and sink to the bottom, and upwelling brings nutrients to the surface. The magnitude of cooling during winter helps to determine how deep the lake mixes vertically. 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.

When winter temperatures are warm, mixing tends to occur at more shallow depths, resulting in warmer lake temperatures. In 2020 and 2021, relatively shallow mixing likely contributed to warmer surface temperatures, while in 2019, top to bottom mixing of lake waters led to cooler water temperatures (UC Davis, 2022). Resistance to lake mixing increases markedly even at temperature increases of only a few degrees (Sahoo et al., 2015). Since 1968, the amount of time Lake Tahoe has been in its stratified, 'summer'-state has increased by a month (UC Davis, 2022). 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. For example, suppressed mixing may create new thermal niches that introduced species can take advantage of, potentially disadvantaging native species that have evolved under clear, cold water conditions.

The lack of seasonal lake mixing can cause shifts in Lake Tahoe's algal species and their distribution (UC Davis, 2022). When mixing is suppressed, larger algae sink and leave the smallest algae suspended at the surface where they scatter light and decrease 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, 2022). This allows for a better understanding of how factors such as temperature, precipitation, and nutrient and sediment inputs into the lake are changing physical, chemical, and biological processes that affect the lake's clarity. While the average clarity of the lake has been relatively stable over the past 20 years, there is a long-term trend of reduced summer clarity. Because water clarity impacts the amount of light penetration, it has important implications for the diversity and productivity of aquatic life that a system can support. In addition, clear waters are valued for aesthetic and recreational purposes.

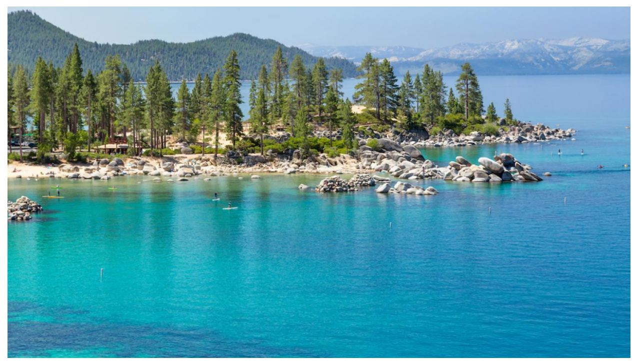


Photo credit: UC Davis/Getty

Lake Tahoe is a crystal-clear high altitude mountain lake, considered one of the jewels of the Sierra. It is known around the world for its water clarity and cobalt blue color. The lake 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. The UC Davis Tahoe Environmental Research Center documents changes in physical and biological parameters to inform management strategies for the lake and its surrounding area (UC Davis, 2021b).

A recent study describes a widespread decline in dissolved oxygen levels among 393 temperate lakes across the US from 1941 to 2017 (Jane et al, 2021). The decline in surface waters was primarily associated with reduced oxygen solubility under warmer water temperatures. By contrast, the decline in dissolved oxygen in deep waters was associated with stronger thermal stratification and loss of water clarity. The authors concluded that despite a wide range of lake and catchment characteristics, the overall trend of lake deoxygenation is clear. Reduced dissolved oxygen in deep water lake habitats may lead to future losses of cold-water and oxygen-sensitive species, the formation of harmful algal blooms, and potentially increased storage and subsequent outgassing of methane.

A decline in the water clarity and ecosystem health of the lake could jeopardize future tourism. The scenic beauty of Lake Tahoe offers cultural and recreational opportunities, such as hiking, skiing, camping and boating. The annual visitor population of about 15 million (California Tahoe Conservancy, 2021) makes it a region of national economic significance, with estimated annual revenues of 4.7 billion dollars (Mooney and Zavaleta, 2016).

What factors influence this indicator?

Lake temperature responses to climate change can vary and in part from the multiple ways in which climate interacts with lake 'heat budgets' (Sadro et al., 2019; Sharma et al., 2017; Woolway et al., 2020). Climate affects lake temperature by increasing heat gains or reducing heat losses. Key drivers controlling lake water temperature are solar radiation, air temperature (influenced by greenhouse gas concentrations), ice cover, cloud cover, humidity, and wind. In addition, suppressed lake mixing (discussed above) can enhance warming of surface waters. Landscape characteristics such as latitude, elevation, and catchment features or land cover can modulate climate effects on individual lakes (Schmid et al., 2014). The climate signal might be further modified by a lake's morphometric attributes, such as lake size and shape, or through differences in the source and magnitude of water inputs (Rose et al. 2016).

A study of lakes around the world found summer air temperature to be the single most consistent predictor of lake summer surface water temperature (LSSWT) (O'Reilly et al., 2015) largely because so many of the factors that control lake temperature are correlated with air temperature. 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, 2022). Since 1912, the average daily *maximum* temperature has risen by 2.25°F (1.2°C) and the average daily *minimum* temperature has increased by 4.5°F (2.5°C). Although year-to-year variability is high, the number of days when air temperatures averaged below-freezing has declined by almost 30 days since 1911. Snow has declined as a fraction of total precipitation, from an average of 52 percent in 1910 to 33 percent in 2020. A warming climate is affecting other physical changes at Lake Tahoe -- including 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 2022* (UC Davis, 2022).

In California lakes that experience ice cover, the amount of snowpack, timing of snowmelt runoff, and ice formation and ice-off (date of ice thawing and breakup) influence lake water temperatures (Melack et al., 2020; Sadro et al., 2019; Smits et al., 2020). For example, Emerald Lake is a high elevation lake in the southern Sierra Nevada that is covered with ice six to nine months of the year. Despite a strong warming trend in regional air temperature over the past three decades, researchers found warming water temperatures occurred only during drought years, when snowpack was reduced (Sadro et al., 2019). Snowpack and lake temperature are strongly correlated in mountain systems likely due to tight coupling between snowpack and ice cover in lakes (Smits et al., 2020). Years with low snowpack at Emerald Lake were accompanied by a reduction in the duration of ice-cover, which acts to buffer lake water from exposure to solar radiation and warming. As snowpack declines in the Sierra Nevada and other mountain ranges (see *Snow-water content* indicator), lake temperature will become increasingly sensitive to warming with reduced ice cover.

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 1968:

(1) at the Index Station (about 0.6 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 20-centimeter 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 through 1996, and since then monthly at 20-centimeter intervals to a depth of 450 meters.

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°C. More recently temperature is measured using a high precision thermistor that is part of a suite of instruments on a Seabird SBE-25plus profiler. Accuracy of the thermistor is 0.001°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 surface 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.

OEHHA acknowledges the expert contribution of the following to this report:

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