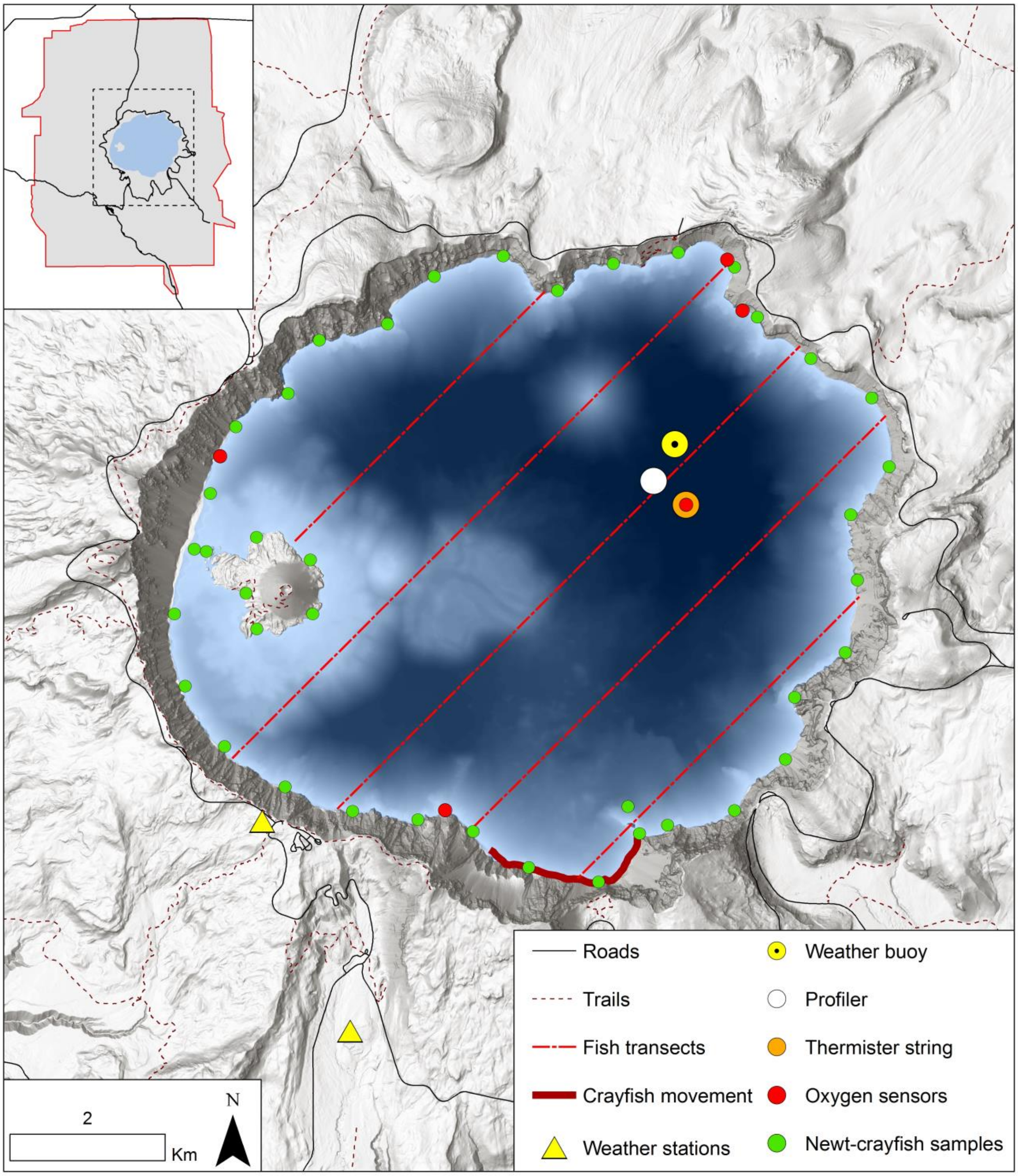
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Crater Lake Long-term Limnological Monitoring Program

State of the Lake Report: 2018



ON THIS PAGE
Map showing some of the long-term sampling and sensor locations throughout Crater Lake.
Map courtesy of the National Park Service

ON THE COVER
Photograph of Crater Lake
Photograph courtesy of Caitlin Hosken and the National Park Service

Crater Lake Long-term Limnological Monitoring Program

State of the Lake Report: 2018

Scott Girdner[1], Mark Buktenica[1], Jeremy Mack[1]

[1]National Park Service
Crater Lake National Park
Crater Lake, OR 97604

March 2019

U.S. Department of the Interior
National Park Service
Crater Lake National Park
Crater Lake, Oregon

Contents

Figures

Tables

Page

Executive Summary

The goal of the long-term limnological monitoring program (LTLMP) at Crater Lake is to ensure the health and preservation of this national treasure. The program serves as a monitoring and research platform to develop and communicate a better understanding of biological, physical, geochemical, and climatological processes that affect the lake. Protected areas like Crater Lake National Park play a key role in answering important questions in ecosystem and earth sciences. Crater Lake's isolation from direct human influence and its protected status within a National Park make it an ideal case-study for how a lake interacts with the surrounding environment and is affected by longer-term changes in climate.

This *State of the Lake Report* presents updated data related to the long-term health of the lake through 2018 and presents our current and evolving understanding of how the lake functions. It includes overall trend-analyses, which are updated on approximately five year intervals (section 2.0 – Analysis of Long-term Trends). It also includes sections summarizing recent projects that focus on important, emerging issues, such as nearshore algae blooms and testing of novel technologies (section 3.0 – Special Projects). This report is primarily intended to inform park management and the general public about Crater Lake. It is not an exhaustive review of all pertinent limnological literature, but does present examples from other lakes and research studies where appropriate. For a more detailed scientific review, please see the 2007 Hydrobiologia Journal special issue on Crater Lake (http://link.springer.com/journal/10750/574/1/page/1).

As one of the clearest lakes in the world, Crater Lake is widely known for its extreme clarity and stunning deep-blue color. Concern that clarity might be declining was the impetus for initiating long-term studies in 1982. Analyses included in this report reaffirm that Crater Lake does not show a reduction in water clarity over time (section 4.0 – Optical Properties). Moreover, both Secchi disk depth and depth of light penetration indicate a slight increase in clarity over the last 40+ years. Long-term data also shows that clarity can be highly variable from year to year, driven by various factors. In particular, the presence or absence of deep-water mixing in winter and the corresponding upward flux of nutrients are dominant drivers of near-surface algal abundance and water clarity in summer (section 7.0 – Mixing Processes).

The LTLMP has started to focus additional monitoring efforts on nearshore areas of the lake following an algae bloom that occurred in the back of Cleetwood Cove in fall 2016 (section 3.0 – Special Projects). This particular event appeared to be associated with calm wind conditions, over several days, and was quickly dissapated when winds increased. In 2017 and 2018, to determine spatial distribution of algae around the entire nearshore area of the lake, we towed our CTD instrument around the shoreline. Temperature and algal abundance from the towed transects showed more spatial variability than expected with elevated algae on the north and west sides of the lake. Unfortunately, a towed transect that takes 5 hours to complete is inherently not designed to capture short-term fluctuations driven by wind and surface currents. In 2018, four year-round instruments were installed at nearshore locations around the lake to investigate mechanisms affecting nearshore algae. Preliminary data from summer 2018 supports the towed transect results showing higher algal production on the north and west shores. It still remains to be seen whether the distribution of non-native crayfish, warmer surface waters, wind events, or some other factor influences the frequency, duration, and magnitude of nearshore algal blooms.

One of the most significant long-term trends documented at Crater Lake involves increases in air temperature and the corresponding impacts on lake thermal structure (section 5.0 – Climate and section 6.0 – Thermal Properties). Increases in summer air temperature influence three fundamental properties of the lake: 1) an increase in summer surface water temperature by 2.9°C (5°F) since 1965; 2) earlier onset of stratification in spring by approximately 33 days; and 3) a 47% reduction in the average thickness of warm water floating on the surface in summer (thermocline depth). Overall, 2018 was another warm and dry year at Crater Lake with the 10th lowest snow pack, 6th earliest snowmelt, and 13th warmest average summer air temperture on record (since 1931). Onset of stratification was the 12th earliest (45 years), thermocline depth the 10th shallowest (37 years), and summer surface water temperature the 5th warmest (53 years). Trends in thermal properties are critical to recognize because they can affect various other lake processes and parameters. Similar changes in thermal structure due to warmer air temperature have also been noted in other large lakes of North America, Europe, and Asia.

Unlike thermal properties, which indicate significant trends through time, biological variables are more variable or exhibit cyclic change (section 8.0 – Biological Properties). For example, abundance of non-native fish has shown 9-10 year cycles, from very low, to relatively high density (up to 24 orders of magnitude). As a result, zooplankton exhibit similar cycles. The monitoring data show that predation from kokanee salmon controls *Daphnia* abundance, the lake's largest zooplankton. An important biological component of the nearshore area of the lake that has shown a signficant increase is non-native crayfish and subsequent decline in the endemic Mazama newt. Signal crayfish have expanded dramatically over the last decade and are having serious impacts on native taxa. Crayfish have spread to nearly 80% of the lake shoreline while newts have disappeared from most of these same areas. Crayfish, and their impact on newts, has been the focus of collaborative studies with the University of Nevada Reno and the U.S. Geological Survey (USGS). These studies have shown that newts in Crater Lake are genteically distinct from newts outside the caldera and consequently have been proposed as a distinct sub-species. Studies indicate multiple replacement mechanisms may be at work. Continued spread of crayfish will likely lead to further declines in newt abundance and distribution, and perhaps elimination.

As mentioned above, mixing of the lake in winter is an important process that affects nutrient availability and the biomass of algae and water clarity the following summer. Deep-water mixing is also the critical process that replenishes oxygen at the lake bottom that is otherwise depleted by decomposing algae raining down from above. Long-term monitoring shows that some winters are already too warm for deep mixing to occur. Detailed modeling by the USGS Oregon Water Sciences Center predicts that the frequency of deep-water mixing over the next 100 years could be greatly reduced or eliminated depending on how quickly air temperature rises. Profound ecological changes to Crater Lake could occur if deep-water mixing ceases.

The LTLMP has long recognized that studying Crater Lake during fall, winter, and spring is crucial for understanding the health and functioning of the lake. As a result, the monitoring program has incorporated year-round sampling, using high-frequency, autonomous sensors. In 2013, an innovative, state-of-the-art profiling instrument was added to the program (section 9.0 – Year-round Lake Monitoring). This instrument provides unprecedented detail both vertically within the water column (every 1 m), and over time scales (daily, year round) that are simply not feasible with traditional boat-based sampling. Similarly, dissolved oxygen sensors installed in 2018, and discussed above, provide a level of detail that can be used to better understand year-round algae production, which in Crater Lake, is typically low. Dissolved oxygen can act as a "canaray in a coal mine" for the overall health of a lake. By adding this type of monitoring to the LTLMP, especially at a large spatial scale, we have added another tool that allows us to provide managers the best information needed to preserve the resources of Crater Lake.

RV Neuston docked at Wizard Island, Crater Lake National Park.

Acknowledgments

The long-term monitoring program is a collective effort by many scientists, managers, summer technicians, and students. We are particularly indebted to the late Dr. Gary L. Larson who retired in 2007 as the NPS and USGS Principle Investigator of the program after nearly 25 years. Gary’s direction and leadership set the stage for the successful and creditable lake monitoring and research program that exists today. We would also like to acknowledge several researchers from the Oceanography program at Oregon State University who have been key partners in integrating monitoring technology and advancing our understanding of Crater Lake. In particular, Robert Collier, Jack Diamond, Chris Moser, Jim McManus, and Greg Crawford. The present monitoring program is funded by Crater Lake National Park.

1.0 Introduction

The overall mission of the U.S. National Park Service (NPS) has been "... to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations" (National Park Service Organic Act 1916). Park managers are therefore tasked with making decisions to preserve the natural resources within parks. One tool that managers can use to aid these decisions, is up-to-date scientific information from long-term monitoring programs that are designed to understand ecological processes and how they respond to natural and anthropogenic influences.

1.1 Long-term Lake Monitoring Program

Limnological studies of Crater Lake occurred as early as 1886. Studies conducted from 1978 to 1981 suggested that water quality might have deteriorated compared to observations made years earlier. A review of existing lake data by the NPS and a panel of limnologists in 1982 concluded that the existing data was insufficient to determine if the lake had actually changed and recommended monitoring to document the basic characteristics of the lake. In the fall of 1982, Congress passed Public Law 97-250 that directed the Secretary of the Interior to conduct a 10-year study on Crater Lake to examine the lake for possible deterioration of water quality.

The long-term limnological monitoring program (LTLMP) at Crater Lake began in 1983 and included four major goals:

1. Develop a reliable database for the lake to be used for comparisons of future conditions.
2. Develop a better understanding of physical, chemical, and biological processes occurring in the lake.
3. Investigate the possibility of short- and long-term changes in the lake.
4. And if changes are found, and human-caused (e.g., pollution), recommend mitigation techniques.

The results from the mandated 10-year program concluded that the lake had not declined in water quality or clarity, within the limits of the methods used and the period of time studied. Additional funding has permitted the LTLMP to continue and expand the scope of monitoring efforts. To date, the LTLMP has spanned 35 years (1983-2018) and has amassed more than 25 datasets that help us understand and preserve the unique system of Crater Lake. The following annual report contains a summary of LTLMP monitoring efforts through 2018 and provides an update on the state of our knowledge and understanding of the Crater Lake ecosystem. This report is primarily intended to inform non-scientists about variables affecting the health of Crater Lake. Possible reasons for some trends are presented using statistical inferences between datasets and comparisons to other lake studies. More detailed analysis and discussion within the context of lakes worldwide is reserved for articles submitted to scientific journals that benefit from editorial peer review.

The first research expedition was conducted off of the research vessel "Cleetwood" in 1886 (NPS photo).

1.2 Crater Lake Overview

Crater Lake is located at the crest of the Cascade Mountains in southern Oregon. The lake partially fills a caldera that formed roughly 7,700 years ago following the eruption of Mt. Mazama (Figure 1). Widely known for its extremely clear water and blue color, Crater Lake is the deepest lake in the United States and 8th deepest in the world. Unlike other Cascade Mountain lakes, Crater Lake rarely freezes over in the winter due to the heat content of the enormous water volume.

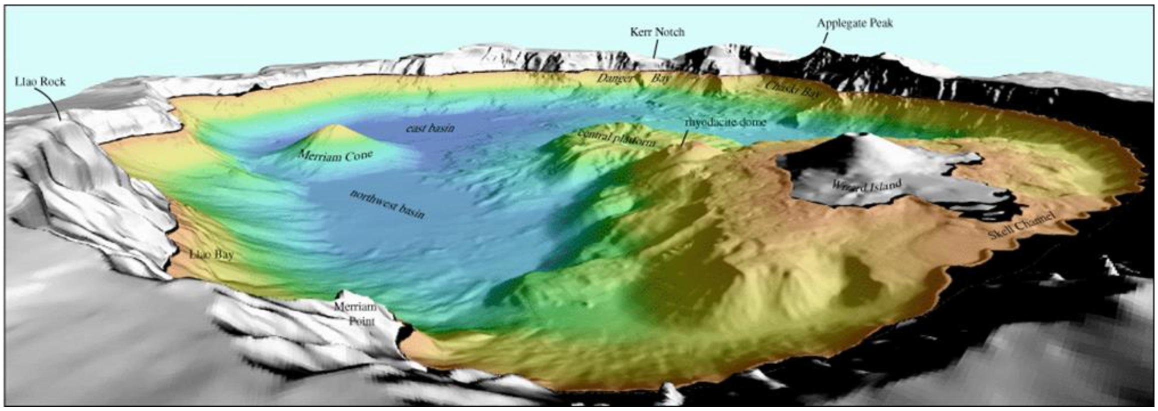


Figure 1. USGS shaded relief perspective image of Crater Lake looking southwest.

Limnologically, Crater Lake is a large dimictic lake which means periods of vertical mixing in fall and spring, thermal stratification in summer and reverse stratification in winter. The lake is extremely unproductive (i.e., ultra-oligotrophic) with peak chlorophyll concentration less than 2 µg/l. The remarkable water clarity allows for a summertime chlorophyll maximum typically between 100-120 m (330-395 ft), which is astonishingly deep for a lake.

Biologically, Crater Lake is home to 160 taxa of phytoplankton, 12 taxa of zooplankton, and larger organisms including kokanee salmon, rainbow trout, signal crayfish, and Mazama newts. The latter is endemic to Crater Lake, whereas the others were introduced to the lake between 1888 and 1941. Although few aquatic macrophytes occur near the surface, a deep-water moss community exists between 26-140 m (85-460 ft) that hangs like icicles on the near vertical walls of the caldera and forms thick fields on gentler slopes around Wizard Island.

Table 1. Characteristics of Crater Lake

Characteristic	Measurement (Metric)	Measurement (Imperial)
Basin	Closed (no outlet)	
Elevation	1882 m	6173 ft
Depth (Maximum)	592 m	1943 ft
Depth (Average)	350 m	1148 ft
Surface area	53.4 km^2	21 mi^2
Shoreline	31 km	21 mi
Volume	19 trillion liters	5 trillion gallons
Precipitation (Average)	165 cm	65 in
Snowfall (Average)	1295 cm	510 in
Secchi depth (Average)	31 m	102 ft
Summer surface temperature (Average)	14 °C	57 °F
Winter surface temperature (Average)	3.5 °C	38 °F

1.3 Sampling Variables

Data monitored as part of the LTLMP can be grouped into four main types (Table 2): biological, physical, chemical, and climatological. The frequency that individual parameters are measured vary from once per year to continuous. For example, acoustic surveys for population estimates of fish occur once in summer, whereas lake temperature is measured continuously using autonomous sensors. Monthly trend data are collected once per month throughout the sampling season, which is normally June through September, with occasional sampling occurring in May depending on the weather. Sampling efforts summarized in the table below allow us to understand the processes that influence Crater Lake. Some sampling has evolved overtime as technologies changed and the below are only a snapshot of the datasets that make up the LTLMP.

Collecting a water sample for dissolved oxygen analysis (NPS photo).

Table 2. Summary of lake monitoring activities at Crater Lake.

Types	Parameter	Measurement	Frequency
Biological	Phytoplankton	Abundance	Monthly – trend, Continuously
		Composition	Yearly
		Growth	Monthly – trend
	Zooplankton	Abundance, Composition	Monthly – trend
	Fish	Abundance, Population density, Condition	Yearly
	Crayfish-Newts	Abundance, Distribution	Yearly
Chemical	Water chemistry	Alkalinity, Conductivity, Dissolved oxygen, Nutrients, pH, Trace elements	Monthly – trend
	Spring chemistry	Alkalinity, Conductivity, Dissolved oxygen, Nutrients, pH, Trace elements	Monthly – trend
Climatological	Weather	Air temperature, Precipitation, Relative humidity, Snow depth, Snowfall, Wind speed and direction	Daily, Continuously
Physical	Water clarity	Secchi depth, light penetration	Monthly – trend
	Water temperature	Temperature	Continuously
	Lake level	Elevation	Daily

2.0 Analysis of Long-term Trends

One of the primary goals of the monitoring program is to identify whether long-term change is occurring in Crater Lake. When measuring natural systems, it often takes many seasons of measurements to distinguish between the range of natural variability and actual long-term change. Most of the Crater Lake datasets are of sufficient duration that long-term trends can be evaluated over the sampling period. This section summarizes the assessment of trends for individual variables using statistical trend analyses (Table 3). We utilize common statistical techniques to detect trends because most parameters we measure have strong variability on a daily, monthly, and/or seasonal basis that mask underlying trends that are not evident by just looking at a scatterplot of data. Seasonal Kendall Test for Trends and Mann-Kendall techniques were chosen because they provide adjustments for serial correlations (daily, seasonal, annual), have less stringent technical requirements for the techniques themselves (normality and equal variance not required), are insensitive to outliers, and are common and accepted techniques for analyzing water quality parameters.

The table below summarizes results of trend analyses for the parameters included in this report. More detailed discussion of the specific variables can be found within this report. Several climatological variables indicate changes, including a trend toward warmer summer air temperature over the period of the monitoring program (since 1983) (5.2) and a reduction in snowpack (5.3). Consistent with the increase in summer air temperature, summer surface water temperature (6.1), onset of stratification (6.3), and thermocline depth (6.5) all show significant trends. Two optical properties, Secchi disk clarity (4.1) and depth of light penetration (4.3), indicate clearer water conditions through time. The only biological variable in the LTLMP indicating uni-directional long-term change is deep-water phytoplankton density represented as particle density (8.1). Other biological characteristics vary widely annually or cyclically (e.g fish and zooplankton), or were not part of long-term trend analyses per se (e.g movement of crayfish and the corresponding decline of the endemic Mazama Newt).

Table 3. Summary of lake monitoring activities

Variable	Measurement	Years	Season	P-value	Trend	Slope
Climate	Night air temperature	1983-2014	Winter	0.76	None	N/A
	Night air temperature	1983-2014	Spring	0.47	None	N/A
	Night air temperature	1983-2014	Summer	0.003	Warmer	0.049
	Night air temperature	1983-2014	Fall	0.33	None	N/A
	April snowpack	1935-2014	Annual	0.046	Lower	-0.143
Optical	Secchi disk depth	1978-2014	Summer	0.028	Deeper	0.082
	Particle density 0-30 m	1988-2014	Summer	0.11	None	N/A
	Depth of 1% light penetration	1980-2014	Summer	0.053	Deeper	0.48
Thermal	Onset of stratification	1966-2014	annual	0.01	Earlier	-0.5
	Thermocline depth	1978-2014	Summer	<0.001	Shallower	-0.241
	Surface water temperature	1965-2014	Summer	0.05	Warmer	0.054
	20 m water temperature	1983-2014	Summer	<0.001	Cooler	-0.050
	100 m water temperature	1983-2014	Summer	0.14	None	N/A
	300 m water temperature	1988-2014	Summer	0.07	None	N/A
	500 m water temperature	1988-2014	Summer	0.003	Cooler	-0.002
Biological	Chlorophyll 0-30 m	1991-2014	Summer	0.28	None	N/A
	Chlorophyll 40-180 m	1991-2014	Summer	0.12	None	N/A
	Primary productivity 0-30 m	1987-2014	Summer	0.22	None	N/A
	Primary productivity 40-180 m	1987-2014	Summer	0.13	None	N/A
	Particle density 0-30 m	1988-2014	Summer	0.11	none	N/A
	Particle density 31-200 m	1988-2014	Summer	0.004	larger	<0.001

3.0 Special Projects

Several new projects have been recently added to the monitoring program. From trying to better understand how an emerging threat to freshwater (i.e., algae blooms) may affect Crater Lake, to exposing Crater Lake's long-term datasets to a broad community of scientists and students, these efforts aim to protect the resources of Crater Lake, as well as, help to address larger-scale, global issues.

3.1 Global Lake Ecological Observatory Network (GLEON)

In 2016, Crater Lake became a site member of GLEON. Established in 2005, GLEON is a network of scientists, information technologists, and engineers with overall goals of (1) building a continental network of instrumented lakes; (2) addressing freshwater issues on local, regional, and global scales; and (3) supporting collaborations for researchers, managers, and students. Today, GLEON consists of more than 500 individual members from 49 countries. The lake network has surpassed 100 sites across all seven continents.

By joining GLEON, Crater Lake increases its involvement with an international community of scientists focused on freshwater issues, similar to those either occurring at Crater Lake, or ones that could affect the lake in the future. Even though the organization has only been around for a little more than a decade, GLEON data has been used in more than 215 professional publications. Crater Lake offers a unique, long-term, database from a system that has minimal human impacts, allowing one to study how natural impacts, such as climate, influence freshwater ecosystems.

Collaboration is keystone to the mission of GLEON. In 2017, with support from the Crater Lake Natural History Association, researchers from Crater Lake attended and participated in GLEON's 19th hands-on meeting in Lake Monhonk, NY. This was an ideal opportunity to interact firsthand with members of GLEON, especially as an international organization, meetings are often held all over the globe and harder to attend. Interest in Crater Lake data was apparent and attendance at the meeting has Crater Lake data involved in several projects, including (1) long-term trends and regulators of dissolved oxygen concentration; (2) impacts of climate on ecosystem services (e.g., zooplankton and fish communities); (3) applying high-resolution data to understand subsurface peaks in algae; and (4) the impacts of the timing of spring runoff on lake productivity.

GLEON conference held in Lake Monhonk, NY, included large group presentations and smaller working groups (NPS photos).

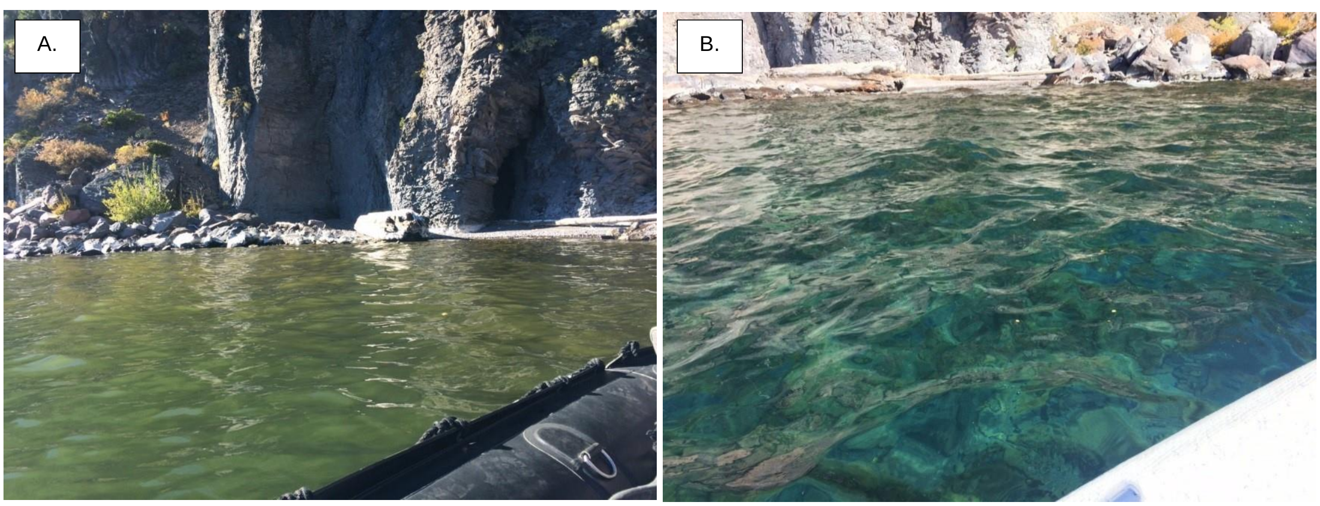
Another important aspect of GLEON is graduate student involvement. Graduate students play an important role by leading many of the working groups and projects. They not only gain experience with collaboration, but benefit by having access to data that often leads to publication, which helps in pursuit of their advanced degrees. Crater Lake is currently working with a GLEON graduate student on a project to model the long-term shallowing of the mixed layer in the lake (section 6.5). This collaboration has led to the submission of a manuscript, but also the creation of a statistical model that can be applied to additional datasets that are a part of Crater Lake's long-term monitoring program.

3.2 Nearshore clarity: Algae blooms

In late September 2016, an algae bloom turned the clear blue water of Crater Lake into a yellowish-green along the north shoreline around Cleetwood Cove. This was the first time that such a bloom was documented in Crater Lake. There is increasing occurrence and awareness of algal blooms in lakes around the country, including Lake Tahoe and local lakes such as Klamath, Diamond, and Lost Creek. A water sample from the bloom showed that the cloudiness of the water was due to high numbers of a type of algae called dinoflagellates, which are notorious for forming blooms. Dinoflagellates are mobile algae that commonly occur in Crater Lake during the summer. They tend to dominate later in summer when the water is warmer. Because they are mobile, they can migrate toward the surface when the weather is calm. When winds pick up, they are dispersed. In this particular situation, the winds had been calm for several days. After the bloom was first observed on Sept 28, 2016, winds increased overnight and the bloom had been greatly dispersed by the next morning (see pictures below).

Other than wind, the specific conditions that allowed this algae bloom to form are unclear. The bloom may be an indicator of nutrient changes associated with high crayfish numbers along the north shore of the lake. It also could be associated with warmer water temperatures, a naturally occurring short-lived event, or it may be an indicator or some other unknown factor. The LTLMP is working to answer three fundamental questions about nearshore algal blooms in Crater Lake: 1) what is the frequency, duration, and size with which blooms form, 2) how does water temperature, wind speed, and time of year affect bloom formation, and 3) are the locations of blooms around the lake associated with locations of other organisms (i.e. crayfish) or specific areas of the lake (sunny versus shaded).

Because blooms can be short-lived and easily influenced by changes in wind, answering these questions requires measurements at high frequency and high spatial resolution. In 2017, the park provided funding for two instruments that can measure algal density and water clarity many times per day and night. These instruments were installed and tested in June 2018. To gain a better understanding of spatial variability along the shoreline, boat based sampling was used to assess the spatial distribution of algal blooms and water clarity around the entire lake shoreline. This sampling was initiated in summer 2017.



An algal bloom (A) was observed along the shoreline in Cleetwood Cove on September 28, 2016. Conditions had improved by the next day (B; September 29, 2016) as winds picked up and dispersed the algae, increasing the clarity of the water (NPS photos).

3.3 Nearshore clarity: Monitoring spatial distribution of algae

We investigated the spatial distribution of algae along the entire nearshore area of the lake in response to an algal bloom that occurred in fall 2016. Our existing CTD instrument package, which normally samples vertically in the water column, was modified so that it could be towed alongside the research vessel. The instruments continuously measured water clarity, algal fluorescence, and water temperature. We collected data in August 2017 and July 2018.

Sampling of water temperature and chlorophyll fluorescence in the nearshore of the lake on July 26, 2018 showed more spatial variability than expected (Figure 2). Water temperature ranged over 5°C (16.3-21.8°C) around the shoreline and chlorophyll fluorescence ranged from 0.224 to 0.537 µg/L. Spatially, fluorescence was higher on the north and west side of the lake and had pockets of elevated levels in cove-like areas along the shoreline.

Equipment and setup of CTD sensors for a near shore tow along the shoreline of Crater Lake (NPS photos).

Figure 2. Temperature (A) and fluorescence (B) data collected from nearshore areas of Crater Lake on July 26, 2018.

3.4 Nearshore clarity: New technology to monitor algae growth

Two ways to track algae growth are to measure dissolved oxygen (DO) in water, which algae create during photosynthesis, or the algae themselves, either by chlorophyll concentration or particle density. In 2018, the monitoring program tested new, high-frequency, sensors that are able to track small scale changes, over short time periods (every 10 minutes), for long periods of time (more than 365 days). These sensors were attached to four moorings installed in nearshore areas of the lake (Cleetwood Cove, Palisade Point, Eagle Point, and Devils Backbone), as well as, to a pre-existing mooring near the middle of the lake.

Data from the DO sensors were analyzed using a new method, known as the diel-oxygen method. This technique uses daily fluctuations of DO to calculate gross primary production (GPP; i.e., oxygen increase) by algae during the day, respiration (R; i.e., oxygen decrease) at night, and the difference between the two, which is known as net ecosystem production (NEP). Hourly weather data (e.g., wind speed) are used in the calculations to adjust for the physical exchange of oxygen at the air and water interface. Figure 3 shows one week of DO readings in September measured at Cleetwood Cove. Daily fluctuations are evident and one would expect these fluctuations to greatly increase during an algae bloom, depending on the size of the bloom.

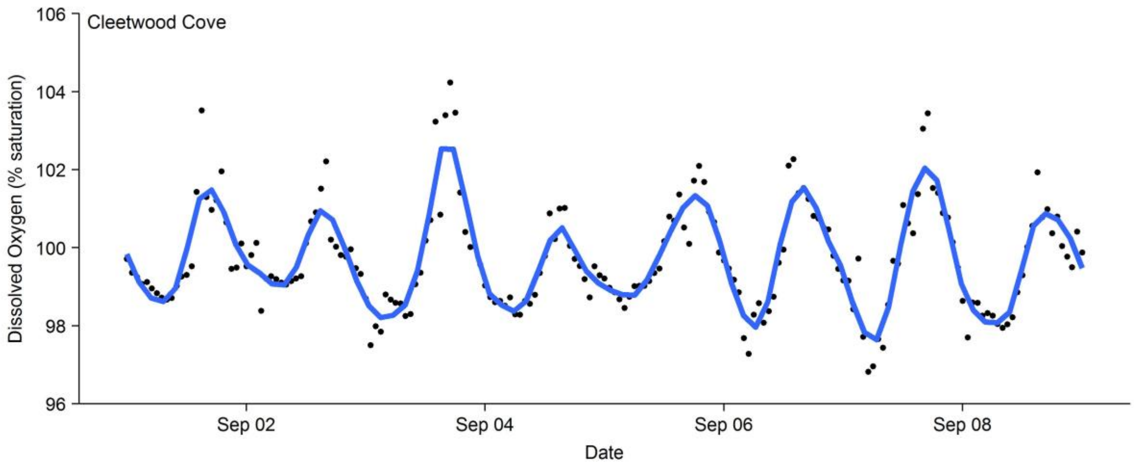
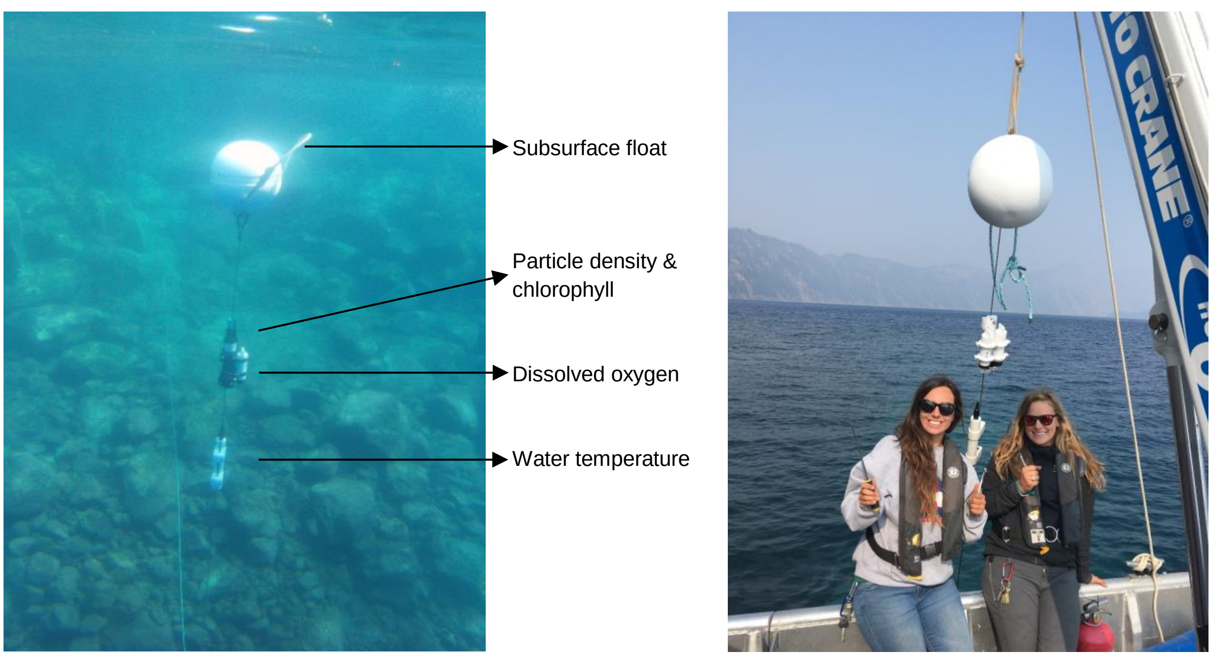


Figure 3. Hourly dissolved oxygen concentration measured at Cleetwood Cove, September 1-8, 2018. Blue line represents fit of locally weighted regression (bandwith=0.2).



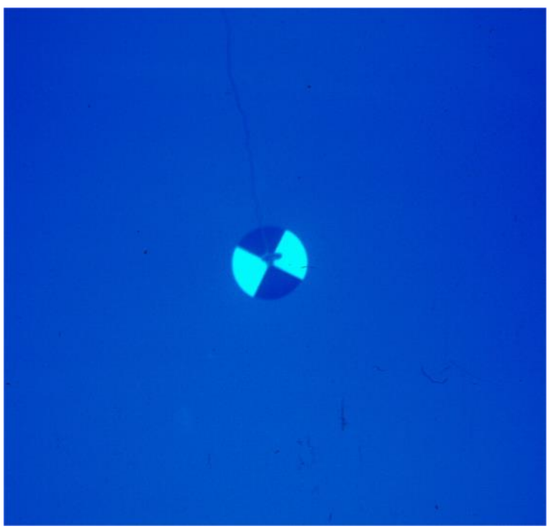
Underwater mooring with high frequency sensors attached. Deployment and collection requires the use of the research vessel crane (NPS photos).

4.0 Optical Properties

4.1 Water Clarity: Secchi Depth (since 1978)

The Secchi disk has been used to measure water clarity in lakes and oceans around the world since the 1860's. Father Pietro Angelo Secchi, an advisor to the Pope, is credited with developing and testing the disk in 1864 as a way to measure the transparency of the Mediterranean Sea. The depth at which the simple round disk disappears is known as the Secchi disk depth. At Crater Lake, the Secchi disk depth is calculated as the average of three descending depths where the observer loses site of the disk as it is lowered into the water and three ascending depths, where the observer regains site of the disk as it is raised. To standardize the process, measurements are only taken between the hours of 10:00 am and 2:00 pm, and only when the lake surface is calm. Crater Lake is known to be one of the clearest lakes in the world with an average summer Secchi disk readings of 30 m and a maximum individual reading of 41.5 m.

The first clarity measurement in Crater Lake was conducted by USGS researcher Joseph Diller in 1896 using a white dinner plate lowered into the lake. Consistent summer measurements have been collected since 1978, prior to the start of the long-term monitoring program. Although there can be high year-to-year variability, Secchi clarity has not declined through time. If anything, readings have become slightly deeper in depth over the study period (Figure 4; $p < 0.001$).



Secchi disk inside Crater Lake (NPS photo).

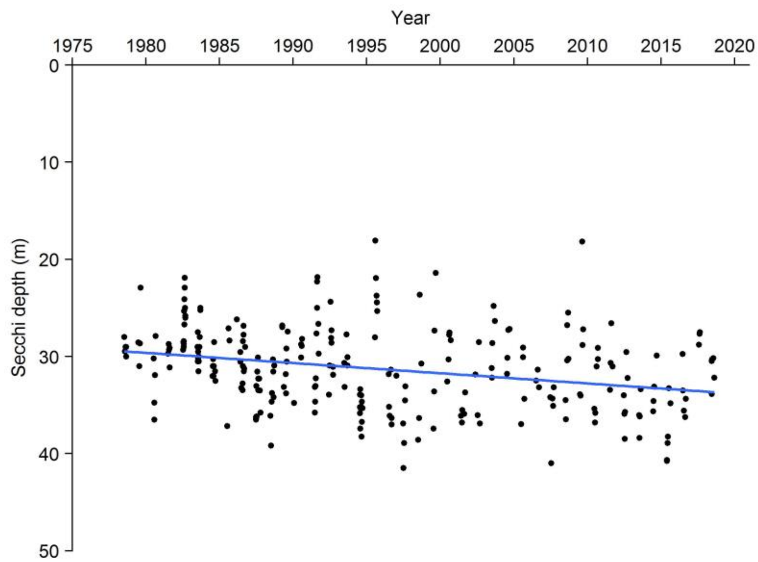


Figure 4. Long-term record of Secchi disk depth in Crater Lake (1978-2018).

4.2 Water Clarity: Particle Density (since 1988)

The beam transmissometer is one of our best tools for measuring water clarity and has been used at Crater Lake since 1988. The instrument provides continuous estimates of particle density as it is lowered through the water column. The advantage of the transmissometer over the Secchi disk is that it can be deployed at any time of the day or night and in any weather conditions. Accurate Secchi measurements must occur mid-day when the lake surface is flat and calm, resulting in fewer occasions when the Secchi disk can be used.

Particles in the water reduce water clarity, whether they are biotic particles (e.g. phytoplankton, zooplankton, pine pollen) or abiotic particles (e.g. dust and minerals from landslides). Although most of the phytoplankton in the lake are below 30 m, it is the density of phytoplankton near the surface that impacts Secchi clarity in Crater Lake. Average particle density in the top 30 m of the lake is highly correlated with Secchi disk depth measured on the same day (Figure 5) and can be used as a surrogate for Secchi disk water clarity. Neither Secchi disk, nor "apparent Secchi," which is calculated from particle density, indicate a decline in water clarity, near the surface, through time (Figure 2, 6).

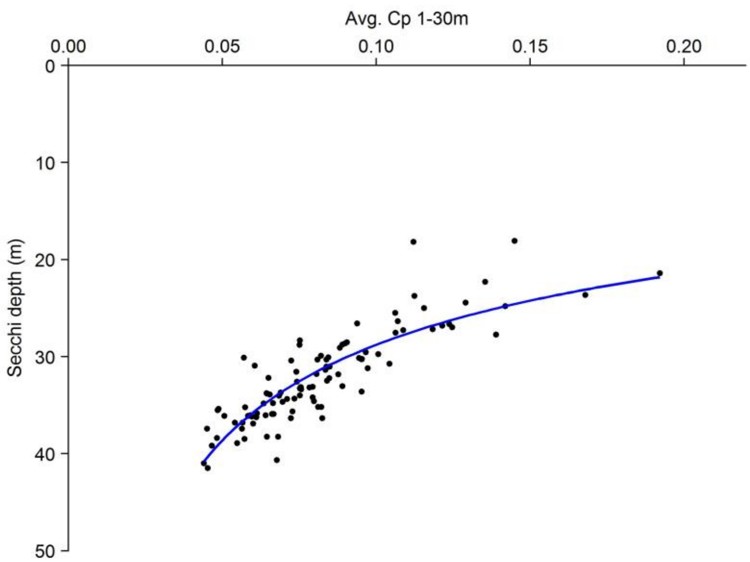


Figure 5. Relationship between average Cp and Secchi depth in Crater Lake.

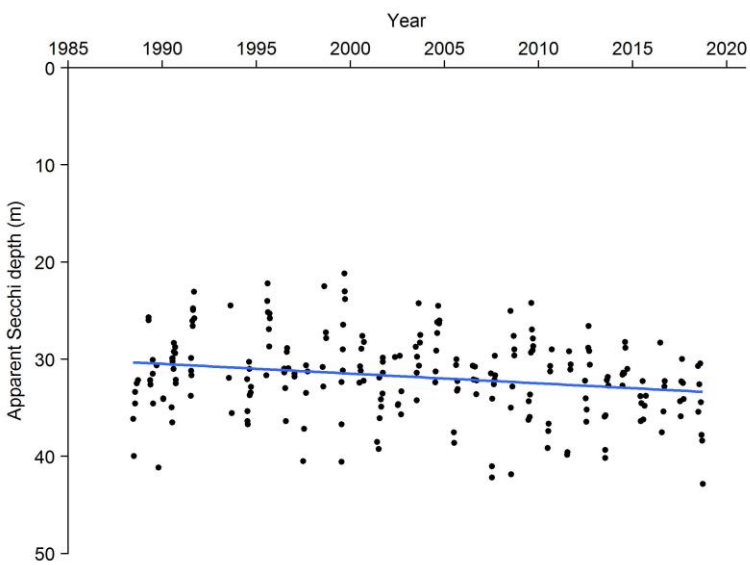


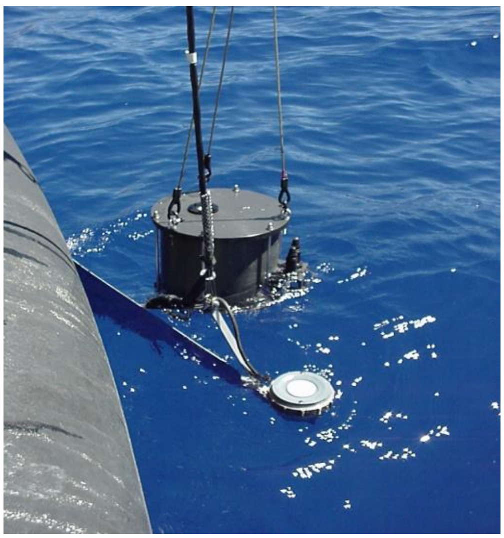
Figure 6. Long-term record of apparent Secchi depth calculated from Cp in Crater Lake (1988-2018).

CTD package used at Crater Lake. Tall black sensors on left and right are transmissometers (NPS photo).

4.3 Water Clarity: Light Penetration (since 1980)

The ability of light to penetrate through water is an important optical property of lakes as it fundamentally affects the vertical distribution of phytoplankton, zooplankton, and fish, the absorption of heat, and the color of the water perceived by your eyes. Light penetrates deeper in clear lakes that have fewer particles like phytoplankton, pollen, or dust. Crater Lake is well known for its remarkable clarity and extremely deep light penetration.

The penetration of light throughout the upper water column of Crater Lake has been measured since the early 1980's. Several instruments have been used over the past three decades as technology has advanced, including a Kahl photometer (1980-1989), Licor scanning radiometer (1995-2009), and Biospherical 8-channel reflectance radiometer (2010-present). The blue wavelength of light (~475 nm) often penetrates the deepest in Crater Lake, part of the reason why the lake appears blue. The depth where 1% of the surface blue-light intensity remains is typically around 100 m in depth in Crater Lake (Figure 7). This is an astonishingly deep depth compared to almost all other lakes. The long-term trend indicates a slight increase in light penetration (P=0.05).



Two of the meters used to measure light penetration in Crater Lake, Kahl photometer in the foreground and the Licor behind (NPS photo).

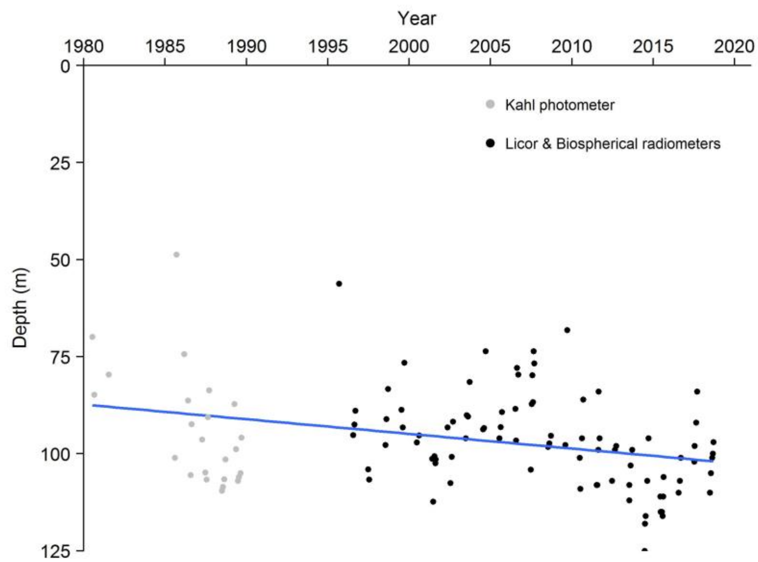


Figure 7. Long-term record of depth which 1% of blue light reaches in Crater Lake (1980-2017).

5.0 Climate

5.1 Present and future air temperature

Meteorological-driven processes exert large and diverse impacts on lakes. Climate is the driving force for a lakes internal heating, cooling, mixing and circulation, which in turn affect nutrient cycling, food-web characteristics and other important features of limnology. Trends in climate are thus potential drivers of trends in various limnological variables. In Crater Lake, air temperature appears to strongly influence the timing of summer stratification, thermocline depth, surface water temperature, near-surface phytoplankton taxa, winter mixing, and vertical nutrient flux.

Figure 8 shows maximum and minimum air temperature that has already occurred at Crater Lake combined with the best available estimates of possible future climate conditions. Although there is a lot of year-to-year variability in the historic data, both maximum and minimum air temperature at Crater Lake showed a period of general decline from the 1930's to the 1970's. Over the last 30 years, minimum temperature tended to increase whereas maximum was more variable.

The predicted temperatures shown below use one of the more moderate climate change scenarios [Representative Concentration Pathway (RCP) 4.5] to estimate conditions at Crater Lake over the next 90 years. Both minimum and maximum daily air temperature are predicted to rise 2-3 °C (4-6 °F) over today's values. Based on these data, average air temperature within the next few decades will become warmer at Crater Lake than any time in the past 86 years.

(RCP data courtesy of Susan Wherry, USGS. These data have been smoothed by using a two-year running average to remove seasonal variation).

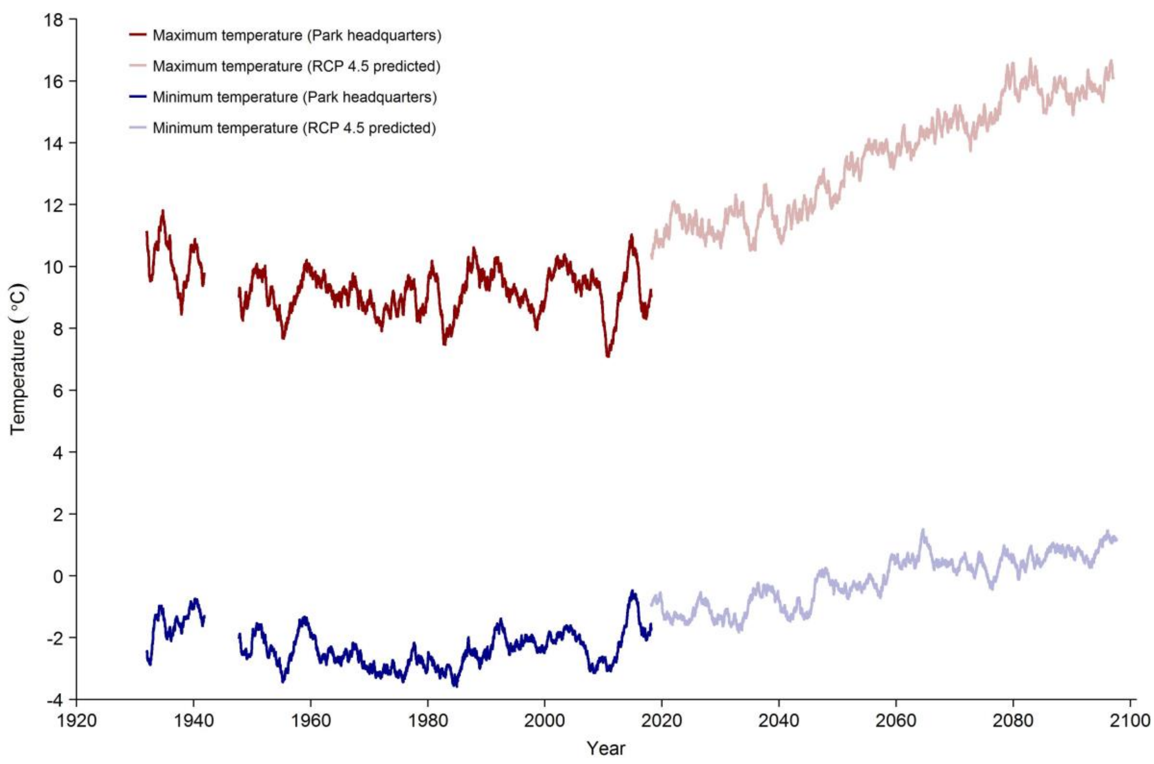


Figure 8. Observed and predicted maximum and minimum air temperatures at Crater Lake National Park headquarters.

5.2 Air Temperature by Season (since 1931)

Long-term changes in air temperature at Crater Lake differ by season (Figure 9A-D). Summer air temperatures play an important role as they influence the thermal structure of the lake during stratification. Summer (Jul-Sep) air temperature at Crater Lake shows a period of general decline from the 1930's through the mid 1970's, followed by a period of increasing temperature to present (Figure 9A). This shift is in close agreement with other studies across western North America.

The increase in average summer temperature since the beginning of the lake monitoring program in 1983 was 1.75 °C (3.1 °F). Although the increasing trend since the 1980's was significant, these air temperatures were still within the range of previous variability recorded at Crater Lake during the first half of the twentieth century. Average summer air temperature during 2018 was the 13th highest on record. Long-term trends in fall temperature shows a slight decline since 1935 (Figure 9B), whereas winter shows a period of general warming since the 1950's (Figure 9C). Spring tends to be quite variable over the period of record (Figure 9D).

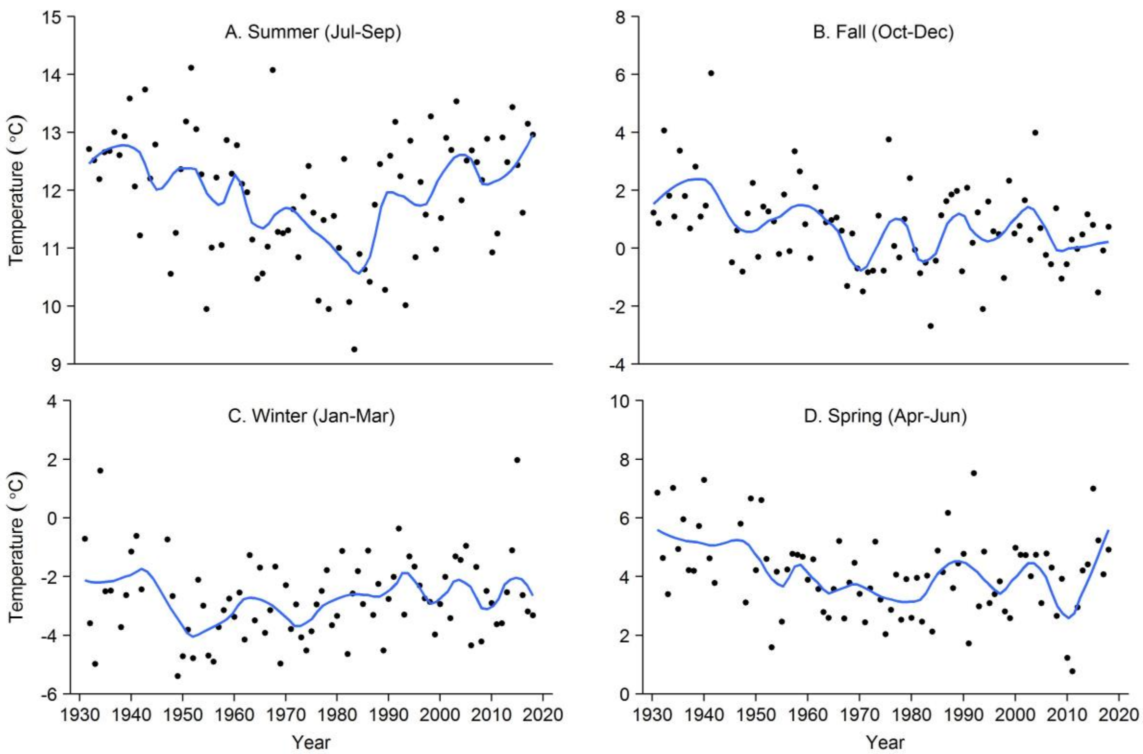


Figure 9. Long-term seasonal air temperature at Crater Lake National Park headquarters (1931-2018). Blue line represents fit of locally weighted regression (bandwith=0.2).

5.3 Snowpack (since 1935)

Many aspects of weather are highly variable from year-to-year, including snowfall and the resulting snowpack. One aspect of snowpack that is commonly measured is the water content, which is the amount of water contained in the snowpack. This measurement is used by water managers to forecast streamflow later in the season. The long-term trend in snowpack water content measured near Park headquarters at the beginning of April indicates a statistically significant decline ($p<0.05$) at an average rate of 1.6 inches (water equivalent) per decade. In terms of actual snow depth, this decline is about 3 inches per decade. Water content has been more consistently below average during the recent decades, beginning in 1990 (Figure 10). This decrease in snow is similar to many mountain areas of the pacific-northwest.

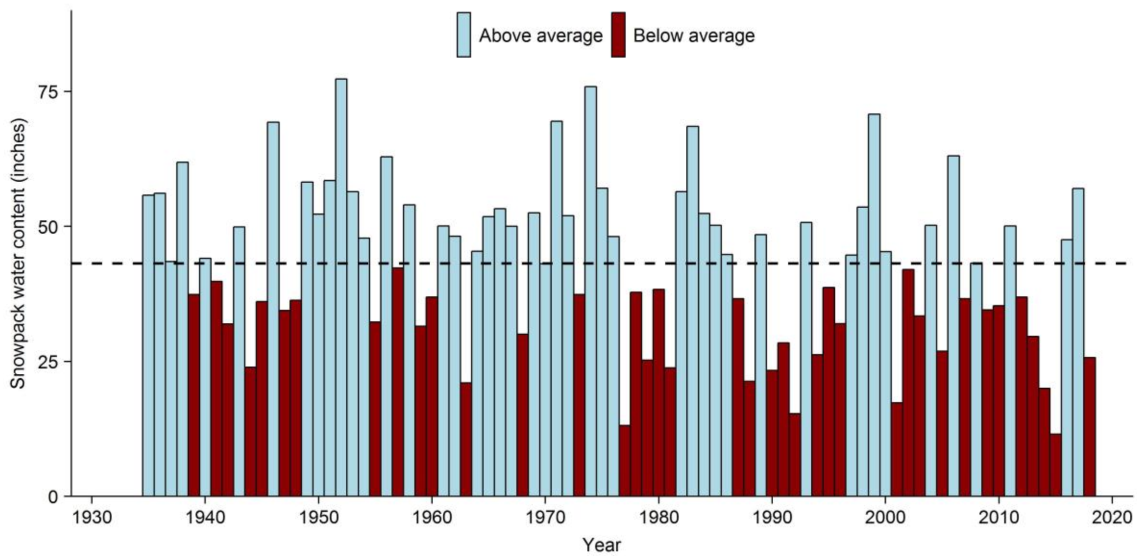


Figure 10. Snowpack water content at the beginning of April at Crater Lake National Park headquarters (1935-2018). Dashed black line represents the long-term average.

Automated weather station encrusted in snow along the rim of the caldera at Crater Lake National Park (NPS photo).

5.4 Climate and Lake Level (since 1961)

Crater Lake acts like a giant leaky rain gauge. The elevation of the lake's surface becomes a balance between loses, from seepage and evaporation, and gains from precipitation. The majority of water input comes from precipitation which falls directly on the lake as rain or snow. A small amount comes from snowpack that builds up on the caldera walls and Wizard Island that enters the lake during snowmelt. Given the difference in seasonal weather patterns, where winter precipitation is modest in intensity, but frequent, and summer precipitation is much less common, and showery, most precipitation occurs as snow. Therefore, winter snowfall has a strong influence on the water level of Crater Lake.

Weather conditions have been measured at Park Headquarters since 1931, with the only significant interruptions during World War II. Measurements of precipitation, snowfall, snow depth, and maximum and minimum temperature are made once daily around 8 AM. Water levels have been measured in some form as early as 1896, when the first of six gauges was installed. Most early measurements were sporadic and from the warm portion of the year when the lake was accessible. Water levels are now continuously measured by USGS, which started their monitoring at Cleetwood Cove in 1961.

Over the period 1962-2019, increases in average lake elevation in a water year (October 1 of the previous year through September 30 of the current year) follow increases in water year snowfall totals (Figure 11). Peaks and dips in surface elevation followed a corresponding peak or dip in snowfall total by approximately two years. There was also an overall decrease, throughout this period, in the rate of both water level and snowfall totals.

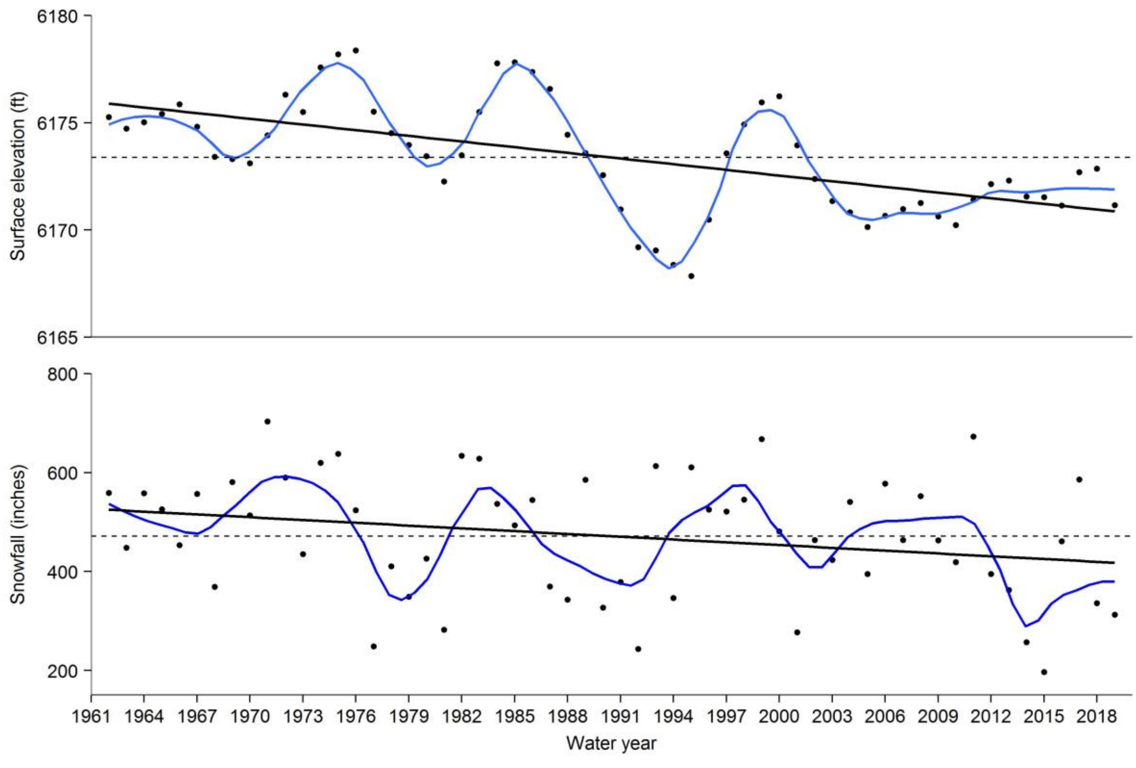


Figure 11. Snowfall (bottom) and surface elevation (top) measurements from Crater Lake National Park, over the period 1962 to present. Blue lines represent fits of locally weighted regressions (bandwith=0.2). Black lines represent fits of linear regression. Dashed black lines represent the long-term averages.

6.0 Thermal Properties

6.1 Summer Surface Water Temperature (since 1965)

The temperature of surface water during summer has increased by 2.9°C (5°F) since temperature records began in 1965 (Figure 12A). In the 25 years prior to 1990, mean summer surface temperature was greater than 14°C in only two years (8%). Since 1990, 68% (19 of 28) of the years were warmer than 14°C.

The increase in surface water temperature appears to be driven largely by an increase in air temperature (Figure 12B). The variation in mean summer air temperature accounts for 73% of the variation in surface water temperature (using linear regression). On average, summer surface water temperature increased 1°C for each 1°C increase in mean summer air temperature.

Increasing summer surface water temperature has been documented in numerous large lakes in North America including lakes Superior, Huron, Mendota, Washington, and Tahoe. Results from studies conducted on these lakes strongly implicated higher air temperature as a primary cause of increasing water temperature, higher air temperature in concert with earlier onset of thermal stratification (Lake Superior), or changes in cloud cover.

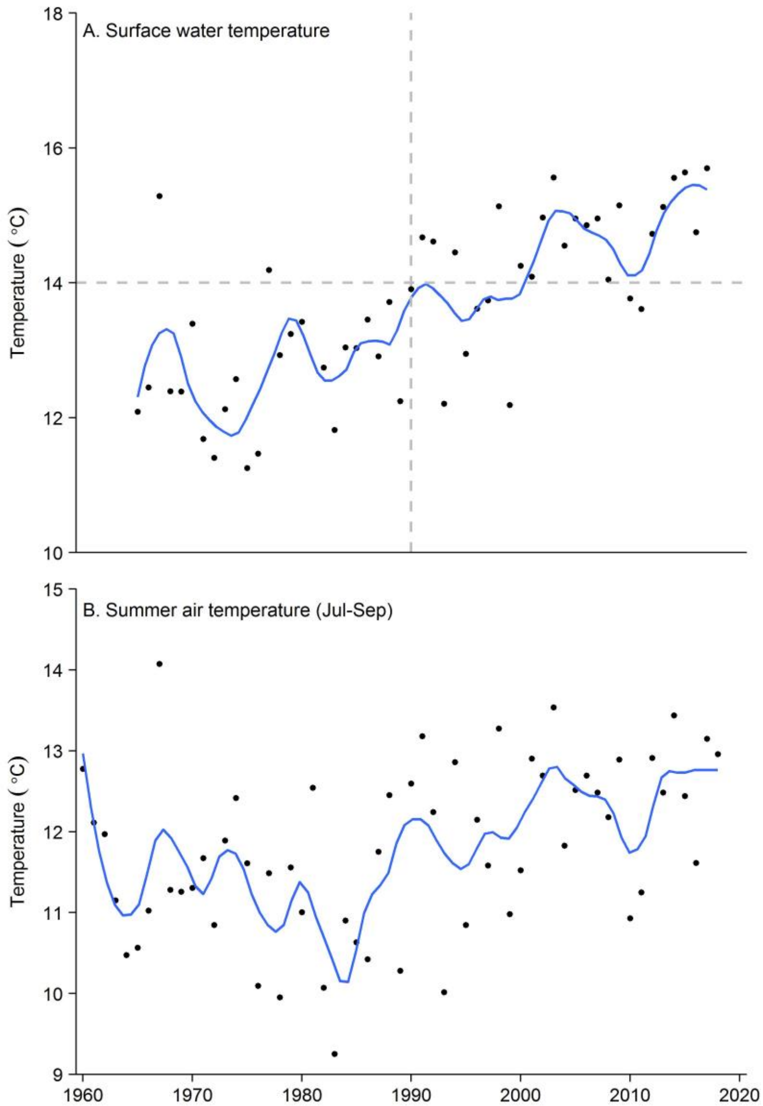


Figure 12. Long-term records of surface water temperature (A) and summer air temperature (B) at Crater Lake National Park. Blue lines represent fits of locally weighted regressions (bandwith=0.2).

Automated weather station attached to a buoy on Crater Lake. The sensor used for tracking surface water temperature is located under the buoy at a depth of approximately 1 meter (NPS photo).

6.2 Summer water column temperature (start date depth dependent)

Long-term trends in summer water temperature are noticeably different depending on depth within the lake. This is because different depths in the water column are affected by air temperature at different times of the year. For example, near surface waters are more affected by air temperature during summer because summer stratification greatly reduces the depth of the mixed layer and effectively seals-off deeper layers. Deeper water tends to be more influenced by conditions in winter and the depth to which the lake mixes.

Surface water temperature (Figure 13; blue) shows a statistically significant increase since 1965 ($p<0.05$) which corresponds with increasing summer air temperature. At 20-m depth (Figure 13; orange), an opposite trend is observed ($p<0.001$). The apparent cooling at 20-m is associated with reduced thickness of warm water floating on the surface (i.e., decrease in thermocline depth). Because thermocline depth has been moving closer to the surface over the same period (section 6.5), the water at 20-m is now more characteristic of the deeper and colder water column than when the monitoring program began in the early 1980's. Water temperatures at and below 100-m (Figure 13; yellow, brown, and black) in the summer are much colder and do not show statistically significant long-term trends or changes. These temperatures are primarily influenced by the depth of mixing in winter.

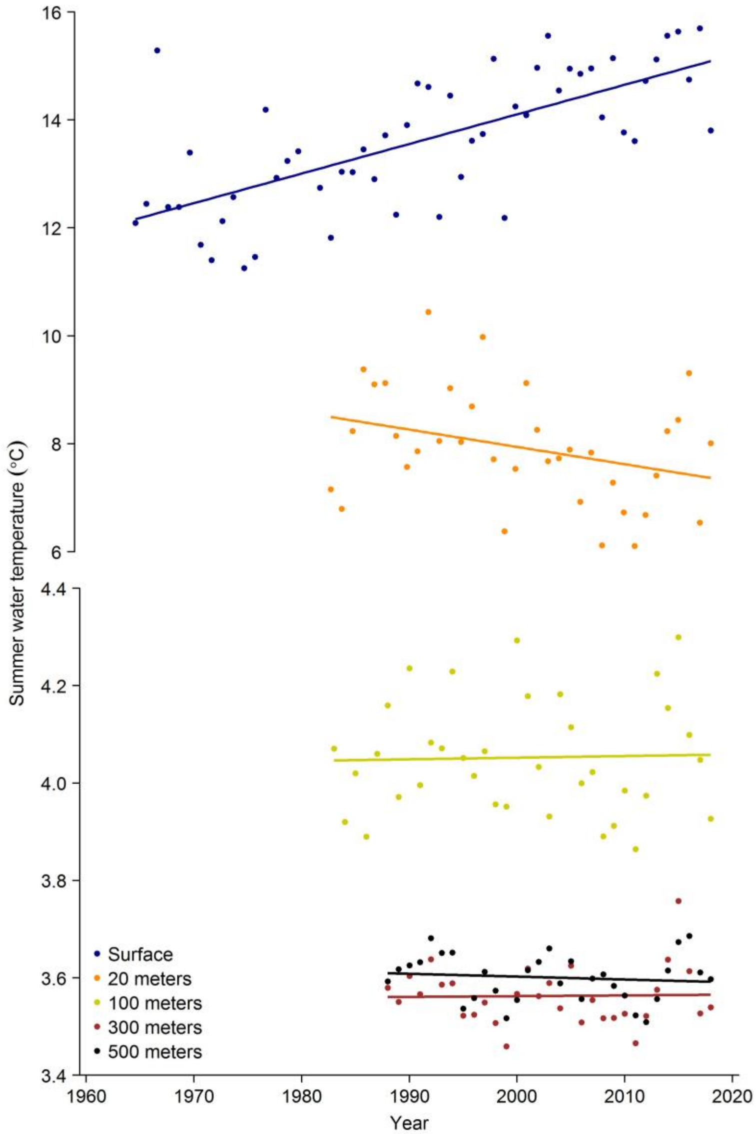


Figure 13. Long-term record of water column temperature in Crater Lake. The length of record is based on depth. For example, the record of surface temperature started in 1965, whereas deep water monitoring began in the late 1980s.

The RV Neuston is the Park's primary vessel for monitoring and research activities. Major renovations were completed prior to the 2017 season (NPS photo).

6.3 Onset of Thermal Stratification (since 1966)

Thermal stratification in summer results in warmer water floating on the lake surface. The onset of stratification signifies the end of vertical mixing of the water column. Ecologically, this shift is important because stratification effectively separates the surface waters from the rest of the lake. The end of vertical mixing also allows phytoplankton and zooplankton to stabilize and grow at discrete depths throughout the water column. Water clarity is also typically highest soon after onset of stratification.

From a long-term change perspective, stratification occurs approximately 33 days earlier today than it did in 1966, albeit with considerable year to year variation (Figure 14). Prior to 1990, stratification began after June 1 80% of the time (13 of 16 years). Since 1990, only 8 of 28 years (28%) began on or later than the June 1 (including 2018). The statistically significant trend toward earlier onset of stratification ($p<0.01$) appears to be driven both by warmer air temperature in the spring and less snow. See section 6.4 for more detail.

The significance of stratification can be seen in Figure 15, which shows algal chlorophyll concentration in the upper 300 meters of the lake over a one year period. Prior to stratification, algae are spread throughout the upper 300 meters because the lake is mixing vertically. As soon as the lake stratifies on June 1st, chlorophyll concentration drops throughout the water column and algae shift to maximum chlorophyll below 100 meters. Consequently, timing of stratification is important to biological, chemical, and physical processes in lakes.

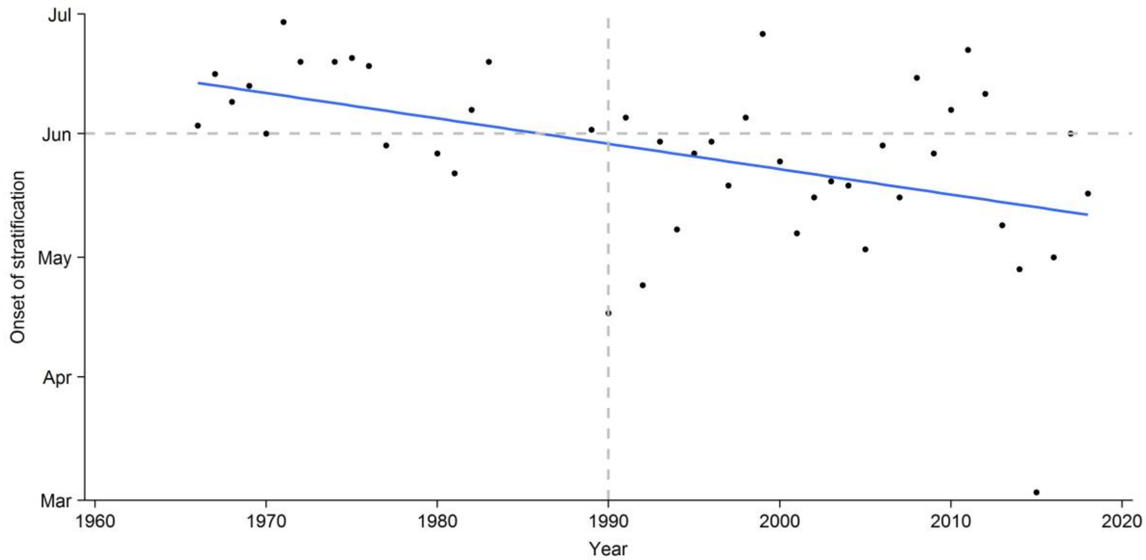


Figure 14. Long-term record of onset of thermal stratification in Crater Lake.

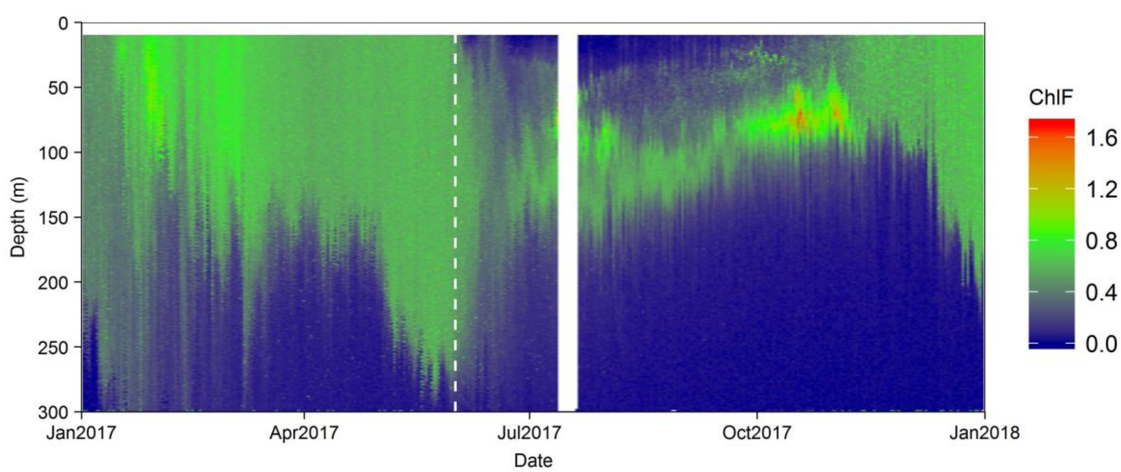


Figure 15. Chlorophyll fluorescence from 1/2017 to 1/2018 in Crater Lake. Dashed white line represents stratification.

6.4 Drivers of Thermal Stratification

The high year to year variation in onset of thermal stratification in Crater Lake appears to be primarily driven by two climate variables: 1) spring air temperature and 2) spring snow depth. These variables account for 76% of total variation in stratification date. Years with warmer spring air temperature allow the water to heat up earlier and result in earlier stratification dates (Figure 16). Similarly, years with less snowpack in the spring stratify earlier (Figure 17). Cold snowmelt water from the caldera walls following heavy snow years appears to delay the onset of stratification similar to the way high inflow from stream discharge can affect stratification patterns in some lakes and reservoirs.

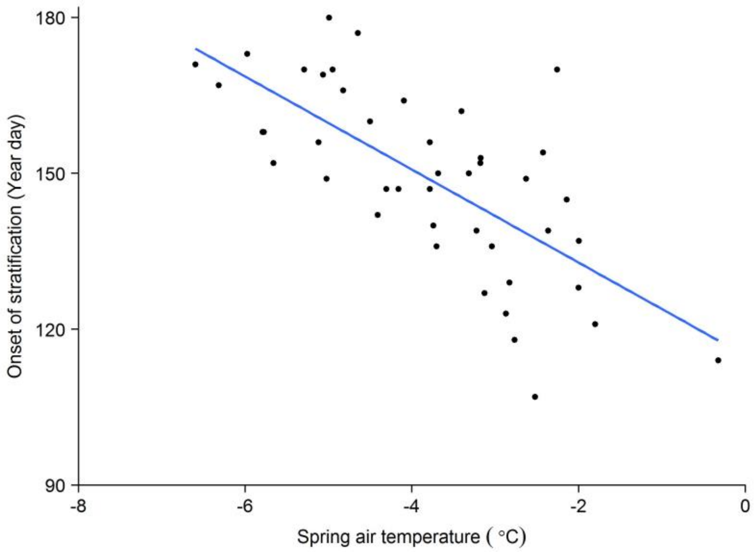


Figure 16. Relationship between spring air temperature and onset of thermal stratification in Crater Lake.

Dr. Robert Collier (Oregon State University) working on the floating weather buoy. The temperature sensor used for tracking onset of stratification is located under the buoy at a depth of approximately one meter (NPS photo).

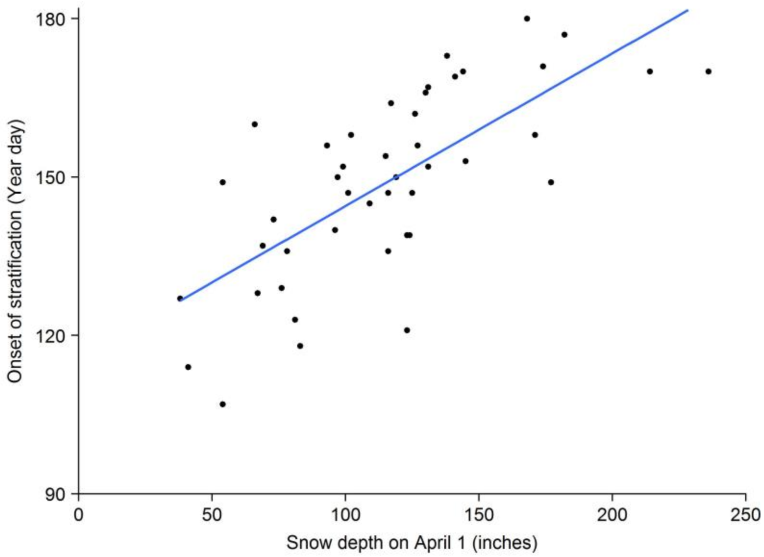


Figure 17. Relationship between snow depth on April 1 and onset of thermal stratification in Crater Lake.

6.5 Summer Thermocline Depth (since 1978)

During summer, warmer water floats on the surface of the lake because it is less dense than the water below. The thermocline is the depth of transition between the warmer water floating on the surface and the colder water below. Figure 18 shows water temperature and thermocline depth in the upper 200 m of the lake over a representative summer-fall period. In summer, the thermocline is usually less than 20 m deep in Crater Lake but increases in depth as the water temperature cools in the fall and wind pushes the thermocline deeper. The depth of the thermocline is important as it determines the amount of warm-water habitat near the surface and thus the distribution of warm water taxa, and it influences the volume of water that interacts with the climate.

Over 40 years, the average thickness of the summer thermocline has decreased by approximately 47% (Figure 19), moving closer to the surface of the lake by more than 6 m (20 feet). The average thermocline depth in 2018 was 6.9 meters, which is the 10th shallowest over the last 41 years. It is currently unclear whether the shallower thermocline depth in Crater Lake is driven by an increase in surface temperature, changes in wind speed, or changes in onset of stratification. Higher water temperature at the surface of lakes could result in shallower thermocline because water becomes more buoyant (less dense) as it warms, making it harder for wind to force the thermocline deeper into the lake. Currently, a researcher from Rensselaer Polytechnic Institute is working on a project to model how climate influences thermocline depth in Crater Lake.

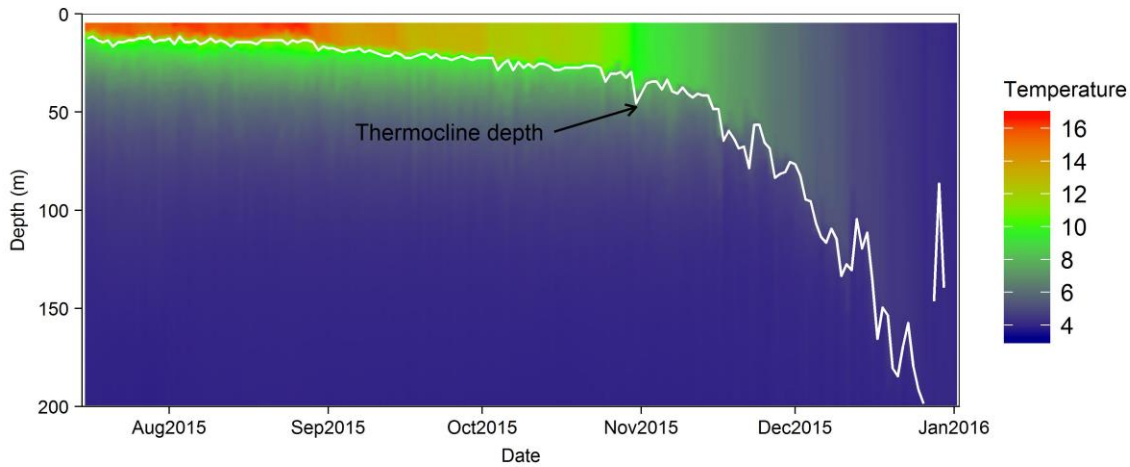


Figure 18. Water temperature from 7/2015 to 1/2016 in Crater Lake.

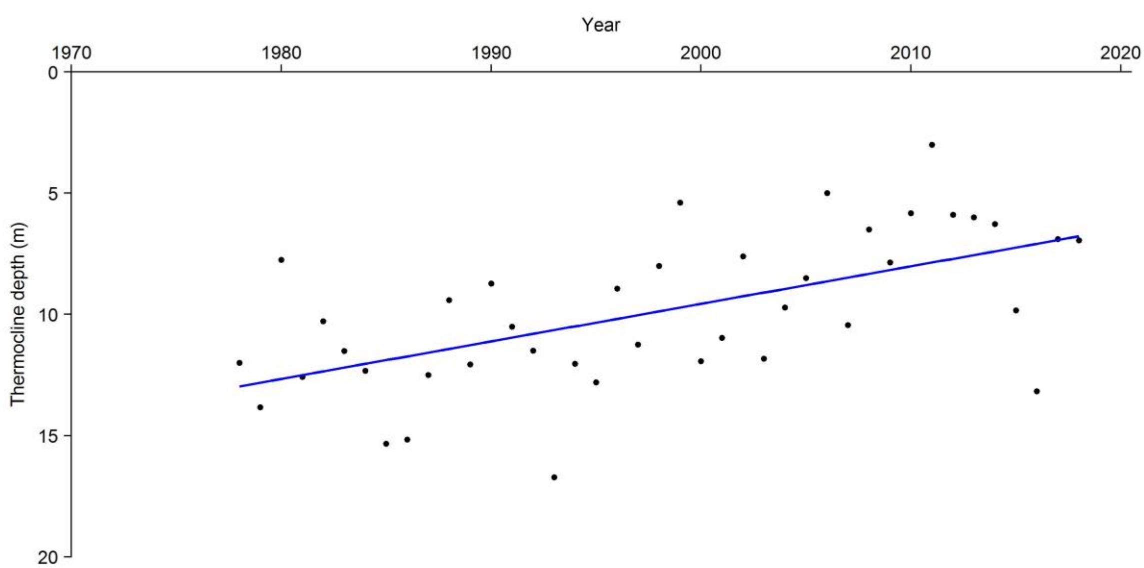


Figure 19. Long-term record of summer thermocline depth in Crater Lake.

7.0 Mixing Processes

7.1 Episodic Deep-Water Mixing Events (since 1992)

Depth, timing, and frequency of vertical mixing are among the most important processes in lakes. In deeper lakes, vertical mixing often controls algal biomass in the upper water column, by redistributing nutrients stored deep in the lake. Vertical mixing also replenishes dissolved oxygen to the lake bottom that is otherwise depleted by decomposition of organic material.

The monitoring program uses detailed water temperature data to track deep-water mixing events. Temperature at the bottom of the lake is variable through time, showing periods of increase due to geothermal heating (Figure 20). Downward spikes indicate mixing events where cold water floating on the surface gets forced down to the bottom through a process called thermobaric instability. Significant mixing events have occurred in 14 of the last 26 years.

Deep-water mixing require reverse stratification of the water column, which occurs when extremely cold water floats on top of the lake. In 2011, reverse stratification is apparent in late February and March, with cold water reaching a depth greater than 200 m (Figure 21; green and blue colors). A mixing event occurred at the beginning of March, characterized by the sudden appearance of colder water at the lake bottom. Sinking cold and higher oxygenated water from above replenishes oxygen at the bottom and displaces deep, relatively nutrient rich water upwards. One concern is that warming air temperatures might prevent reverse stratification and as a result, prevent deep-water mixing events. The loss of deep-water mixing could have profound effects on the ecology of Crater Lake. Personnel from USGS and University of Trento have used modeling techniques to assess how warming air temperature would affect mixing of the Crater Lake over the next 100 years (section 7.4).

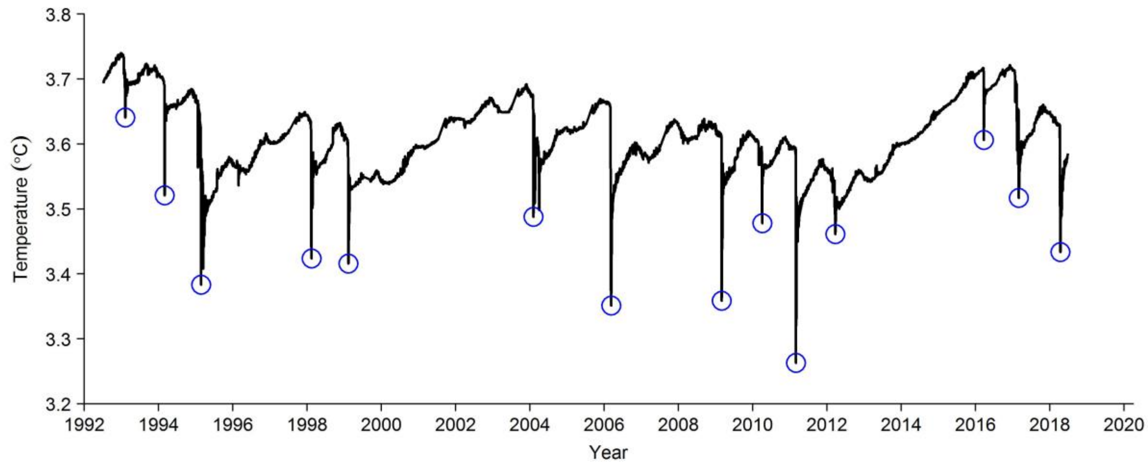


Figure 20. Long-term record of deep-water temperature in Crater Lake. Blue circles highlight deep-water mixing events.

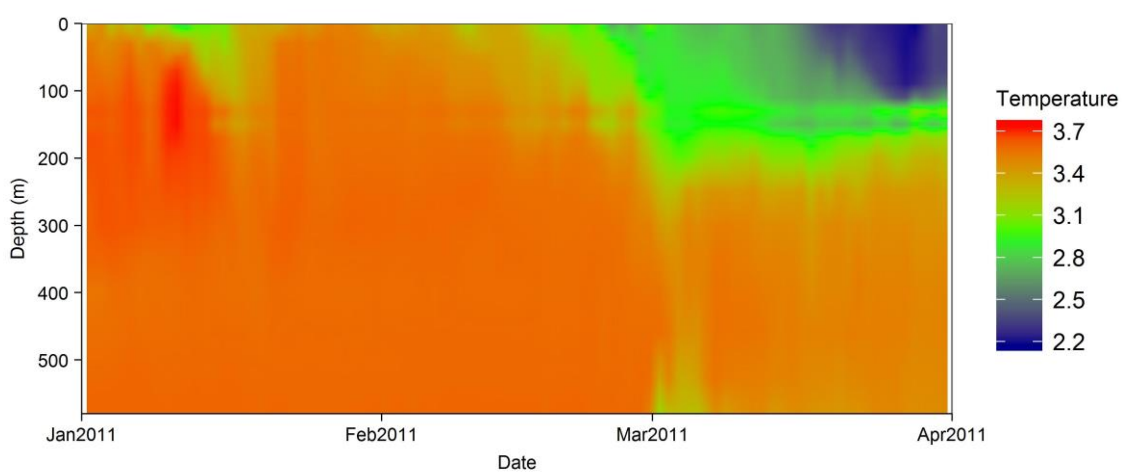


Figure 21. Temperature data showing a deep-water mixing event in 2011 in Crater Lake.

7.2 Influence of Winter Mixing on Deep-Water Nitrate Storage (since 1989)

Winter mixing is important because it controls the movement of nutrients throughout the lake. Nitrate is the primary nutrient limiting algal growth in Crater Lake. Nitrate dissolved in the water is near zero in the upper part of the lake because it is rapidly taken up by phytoplankton (Figure 22A). Nitrate increases with depth because organic material "rains" down into deeper parts of the lake and decomposes, releasing nitrogen, and is not taken up by algae because it is too dark for algal growth.

Over the last 32 years, concentration of nitrate in deeper parts of the lake (Figure 22B) follows the same pattern in deep-water temperature (Figure 22C). Sudden drops in temperature deep in the lake indicate mixing events that coincide with drops in deep-water nitrate levels. In the absence of mixing events, nitrate levels slowly rise due to the decomposition of algae falling down from above and water temperature increases due to geothermal heating from the lake floor (for example 2012-2016). Tracking the vertical movements and deep-water storage of nitrate is critical to understanding the clarity of the lake. Likewise, it is important to appreciate how long-term changes in climate have the potential to influence deep-water mixing in winter and thus effect nutrients.

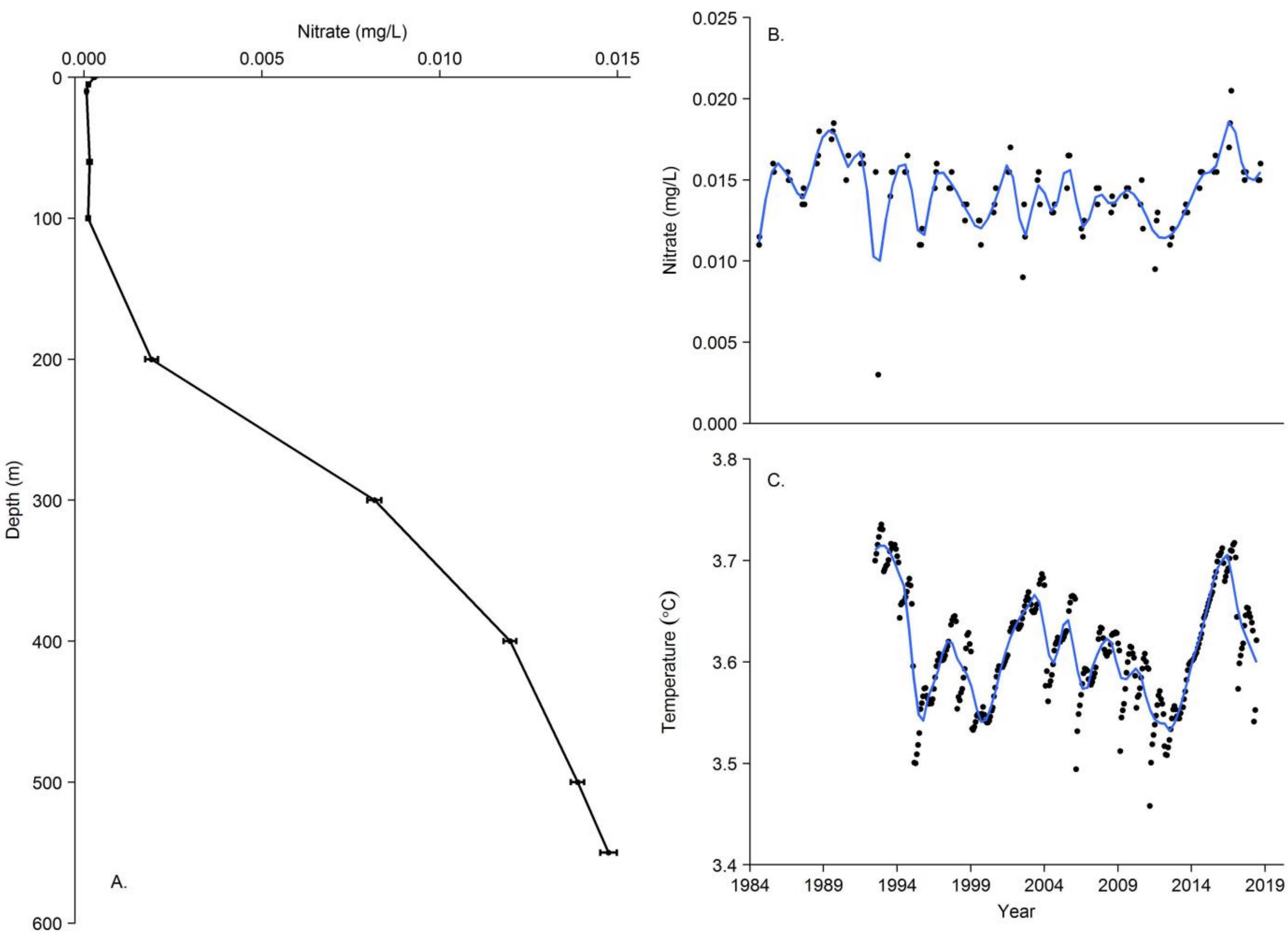


Figure 22. Nitrate dynamics in Crater Lake: (A.) Concentration throughout the water column and (B.) changes in deep-water nitrate concentration with (C.) corresponding decreases in water temperature.

7.3 Impact of Winter Mixing on Surface Water Clarity (since 1988)

Data on particle density, collected over the last 29 years, shows that deep-water mixing, in winter, can reduce water clarity the following summer. When cold water in the upper part of the lake is forced down to deeper waters, nutrients are circulated upward, making them available for the algae growth. Regardless of winter mixing, summer begins with few algal particles in surface waters. As summer progresses, particle density increases more rapidly in years with large mixing events compared to non-mixing years (Figure 23). By August and September, particle density is 45% and 65% higher, respectively, in years with deep-water mixing events.

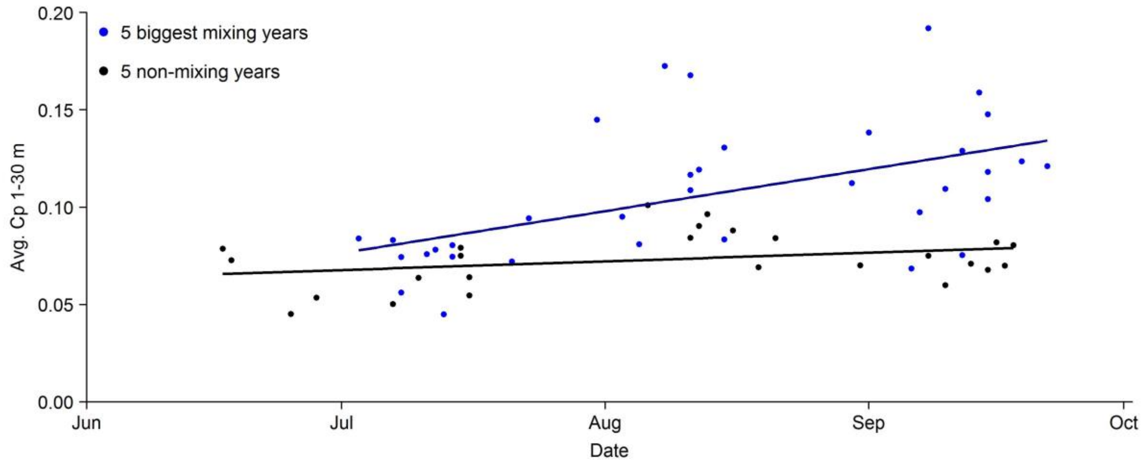
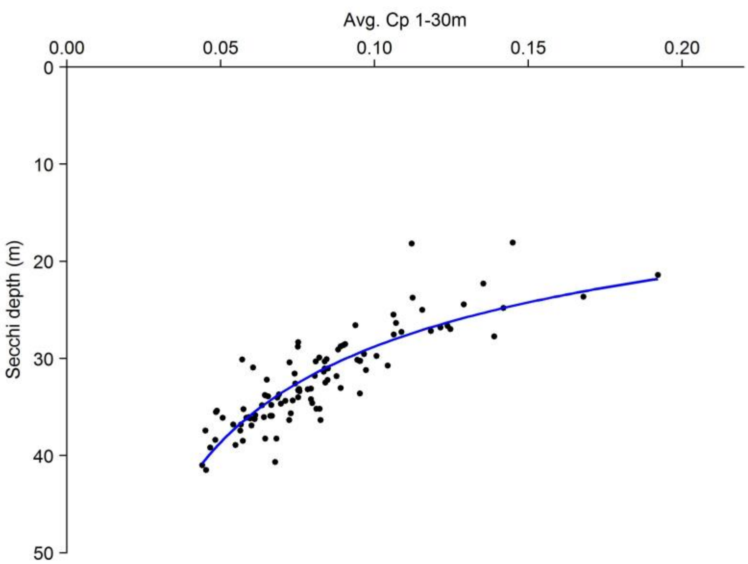


Figure 23. Comparison of average Cp throughout the top 30 m of Crater Lake, after the five biggest mixing years and five non-mixing years.



Secchi Depth < > Particle Density (Cp)

Although much of the algae in Crater Lake are below 30 m, it is the density of algae in near-surface waters that affects Secchi depth. Average particle density in the top 30 m of the lake is highly correlated with Secchi depth measured on the same day and can therefore be used as a surrogate for water clarity (Figure 5; left). Particle density measurements from the transmissometer on the profiling CTD is one of our best tools for studying water clarity.

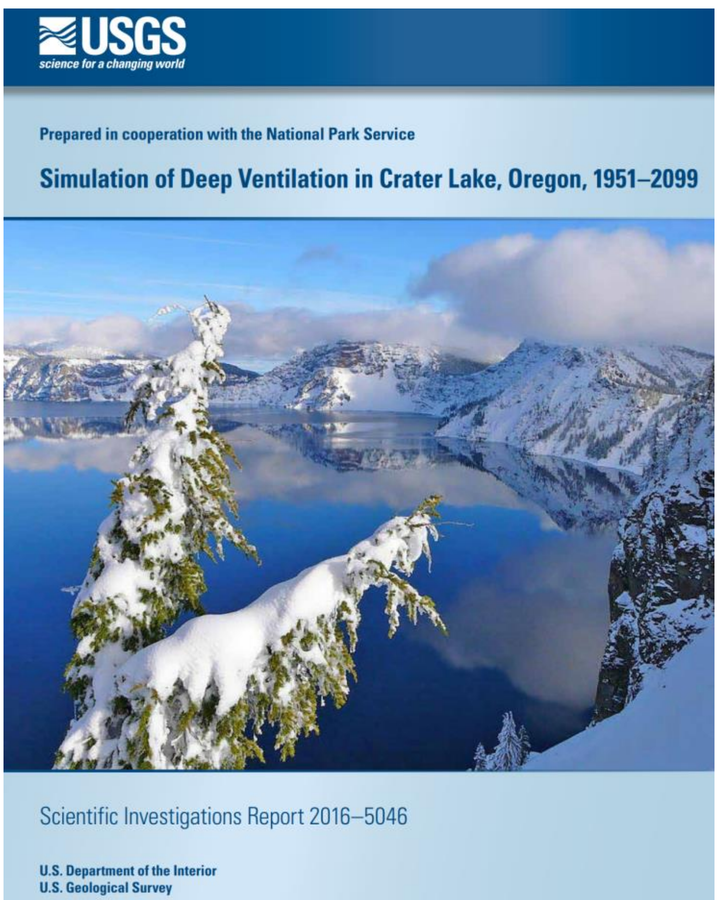
7.4 Predicting Winter Mixing in a Warming Climate

Previous sections highlight the importance of deep-water mixing events on Crater Lake. How will mixing dynamics respond to future climate projections? Researchers from USGS Oregon Water Sciences Center and University of Trento (Italy) used special modeling techniques to address this very question. Using a recently developed computer model, designed specifically for cold, deep lakes, like Crater Lake, they were able to simulate lake dynamics under future climate conditions.

The model uses inputs of weather conditions (e.g., air temperature, wind speed, and solar radiation) and lake geometry to predict water temperature and the frequency of mixing to the bottom of the lake. The accuracy of the model was carefully tested by its ability to reproduce past lake conditions (temperature and mixing) based solely on model inputs. This gives us confidence in its ability to predict mixing under predicted weather conditions. Downscaled global climate change scenarios for the Crater Lake region were used to assess how warmer climate conditions would affect deep-water mixing of Crater Lake over the next 100 years.

The modeling results (Figure 24) show that Crater Lake is indeed vulnerable to major changes in lake mixing in the immediate future. However, the degree to which mixing declines and the speed with which they occur strongly depend on how quickly warming proceeds, especially warming air temperature in the fall and early winter.

See the full peer-reviewed report for more details about the model development, calibration, climate change scenarios used, and effects on deep-lake mixing (Wood, Tamara M., Susan A. Wherry, Sebastiano Piccolroaz, and Scott F. Girdner. Simulation of deep ventilation in Crater Lake, Oregon, 1951–2099. No. 2016-5046. US Geological Survey, 2016.)



Technical report published in collaboration between NPS, USGS, and the University of Trento, simulating mixing dynamics of Crater Lake, given future climate conditions.

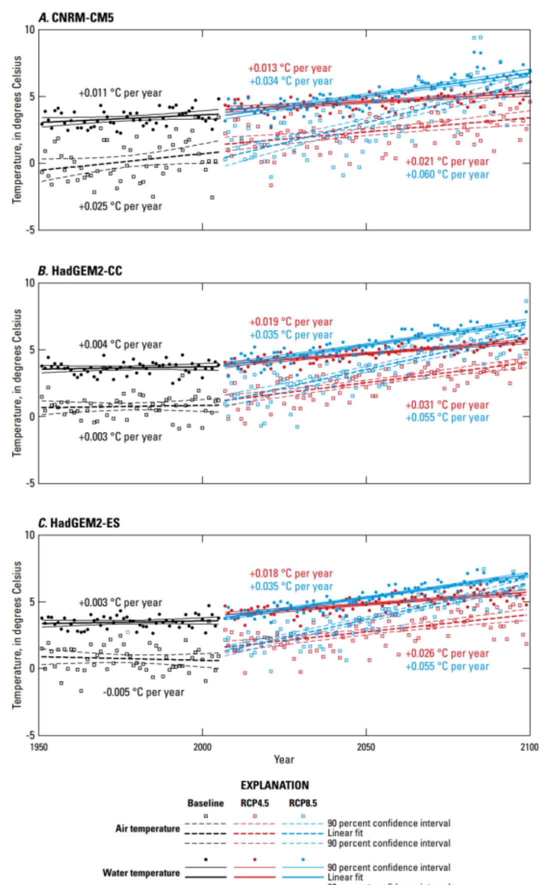


Figure 24. Results of model simulations predicting water temperature in Crater Lake, under future climate conditions.

8.0 Biological Properties

8.1 Phytoplankton Abundance: Particle Density (since 1988)

Particle density is a good proxy for estimating phytoplankton abundance in Crater Lake because phytoplankton are the primary source of particles within the water column. One method of measuring particle density is with an instrument known as a beam transmissometer. This instrument measures the amount of beamed light, reaching a light detector a set distance away. The amount of light that is absorbed or scattered by particles in the water is then used to calculate particle density.

The monitoring program collects data on particle density multiple times per month, typically during summer. Vertical profiles of the entire water column are taken with a beam transmissometer that is attached to a CTD instrument. In Crater Lake, two phytoplankton communities typically develop in summer, one in warm water floating near the surface and a deeper group typically peaking around 60 m (Figure 25). Long-term trend data indicates that particle density of the upper community (1-30 m) has slightly decreased over the monitoring period (Figure 26A; $p<0.001$), while the deeper community has remained relatively constant (Figure 26B).

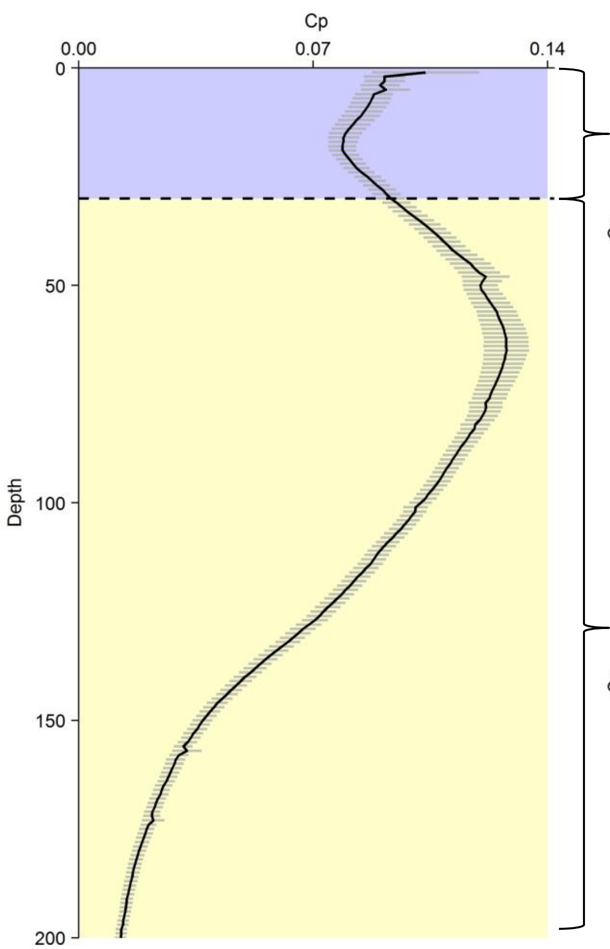


Figure 25. Particle density change with depth in Crater Lake.

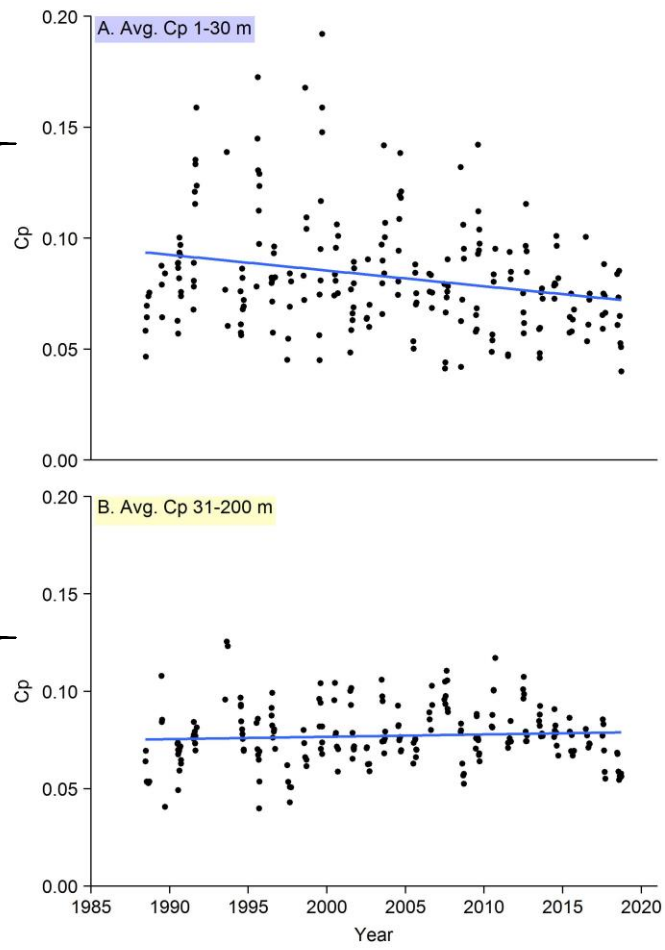


Figure 26. Long-term record of particle density in (A) surface (1-30 m) and (B) deeper water (31-200 m) in Crater Lake.

8.2 Phytoplankton Growth: Primary Productivity (since 1987)

Primary productivity measures growth rate of phytoplankton by estimating carbon uptake (i.e., CO_2 assimilation). Estimates of primary productivity are different from other measures of algae since it is not evaluating the amount of algae directly but rather how much that algal community is growing. The monitoring program uses an *in-situ* $^{14}CO_2$ uptake method, where a known amount of radiolabeled (^{14}C) bicarbonate is added to samples containing a known amount of dissolved inorganic carbon (CO_2). The samples are then incubated at 13 depths within the water column (surface to 180 m). After the incubation period, samples are recovered, treated, and returned to the lab for analysis. Carbon uptake is estimated based on the fact that uptake of ^{14}C is proportional to ^{12}C found in CO_2. Primary productivity estimates (μg C m^{-2} h^{-1}) are calculated for the 13 depths of the lake.

Primary productivity throughout the water column follows a similar pattern seen in particle density – rates peak near the surface and around 60 m, where two phytoplankton communities typically develop in summer (Figure 27). There is a high degree of year-to-year variability in primary productivity, especially deeper in the water column, where rates have slightly decreased over time (Figure 28; blue circles).

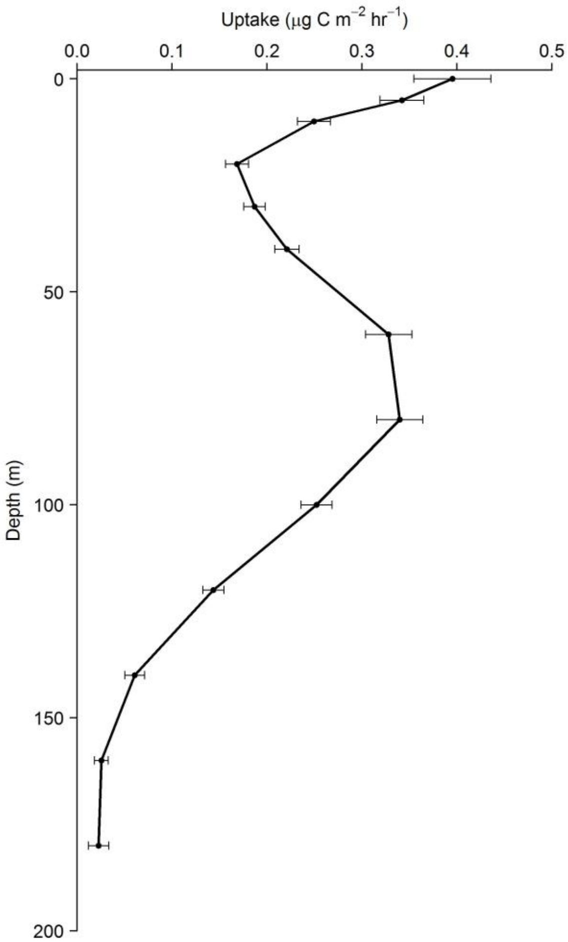
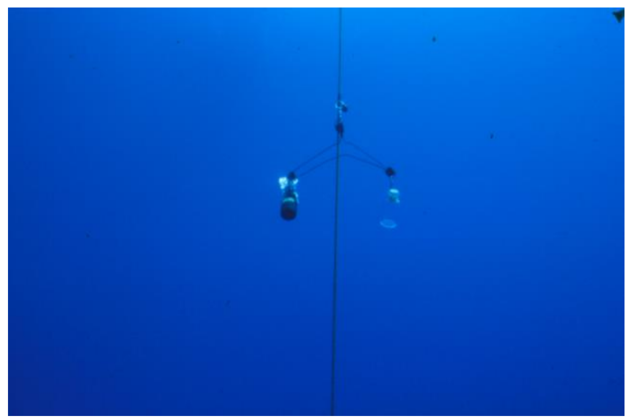


Figure 27. Average carbon uptake (±SE) measured at 13 depths during mid-day in Crater Lake.



Light and dark bottle incubation in Crater Lake (NPS photo).

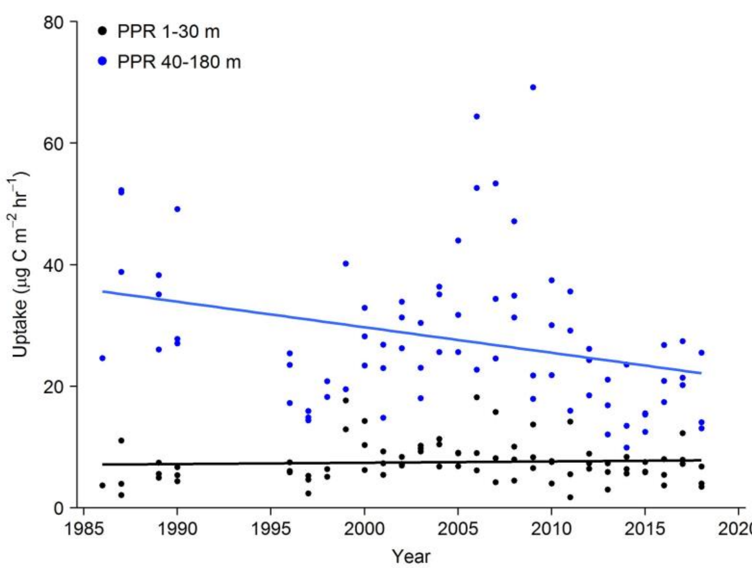


Figure 28. Long-term record of carbon uptake integrated over two intervals: 1-30 m (black) and 40-180m (blue).

8.3 Phytoplankton Composition (since 1989)

Free-floating phytoplankton form the base of the food-chain in deep lakes. They support larger organisms, such as zooplankton, which in turn are food for even larger organisms like fish. In summer, the phytoplankton in Crater Lake form two distinct communities separated by the thermocline. One community inhabits warm water near the surface and are almost completely dominated by a few relatively large diatoms and dinoflagellates (Figure 29A). The second community, which inhabits deeper depths is much more diverse (Figure 29B). Since 1989, the near-surface community has not shown obvious long-term changes except for a possible reduction in Chrysophyta beginning around 1996. Chrysophyta also appear to show long-term reductions in the 60-80 m range.

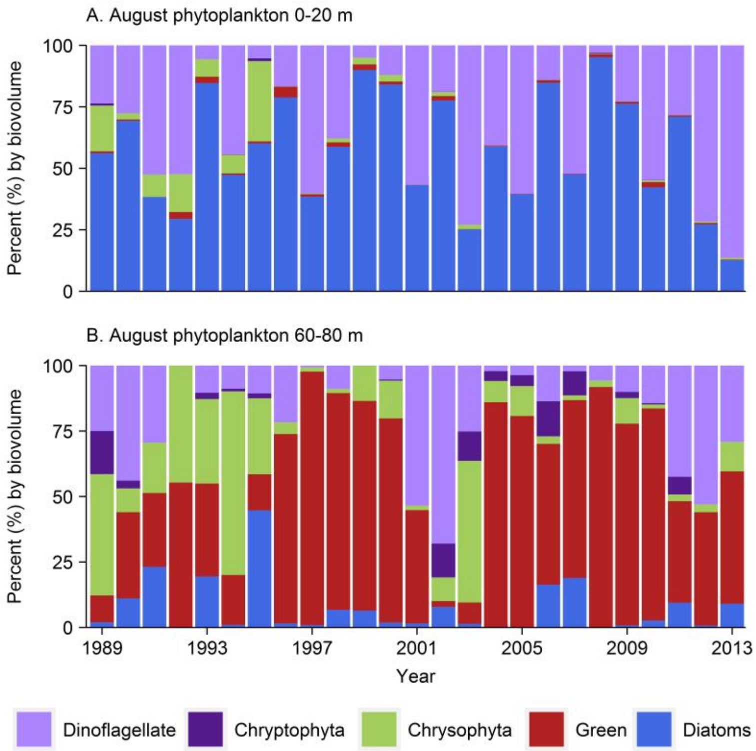
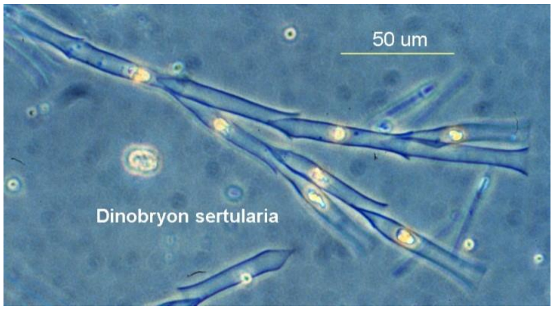


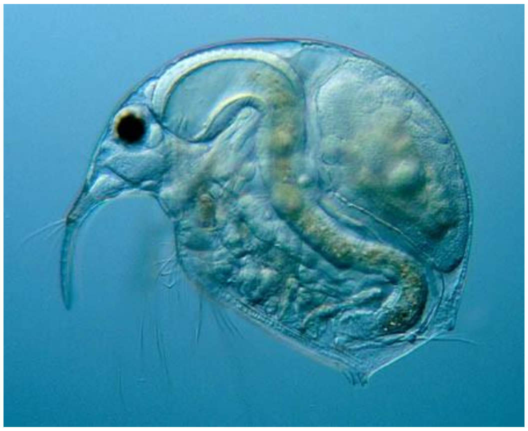
Figure 29. Long-term record of phytoplankton assemblages in Crater Lake in August at two locations within the water column: (A) 0-20 m and (B) 60-80 m.



Microscope image of the chrysophyte algae *Dinobryon sertularia* from Crater Lake (NPS photo)

8.4 Zooplankton Composition (since 1985)

Zooplankton (animal plankton) are collected once monthly during the summer from 8 depth zones in the water column. There are relatively few zooplankton species in Crater Lake: two crustaceans, *Daphnia* and *Bosmina*, and nine rotifers dominate the offshore community (Figure 30). *Daphnia*, known as the water flea, is the lake's largest zooplankter (~2 mm long) and its abundance through time is strongly controlled by predation from introduced kokanee salmon (section 8.5). *Bosmina* is almost always present. Dominance within the rotifer community has shifted from *Keratella cochlearis* early in the monitoring program to one dominated mostly by *Kellicottia* and/or *Polyarthra* for the last two decades. The zooplankton community in Crater Lake is unusual because there are few taxa and no pelagic copepods, a relatively large zooplankter common in other mountain lakes.



Bosmina longirostris (Photo: Florida Sea Grant)

Keratella cochlearis (Photo: Malcom Storey)

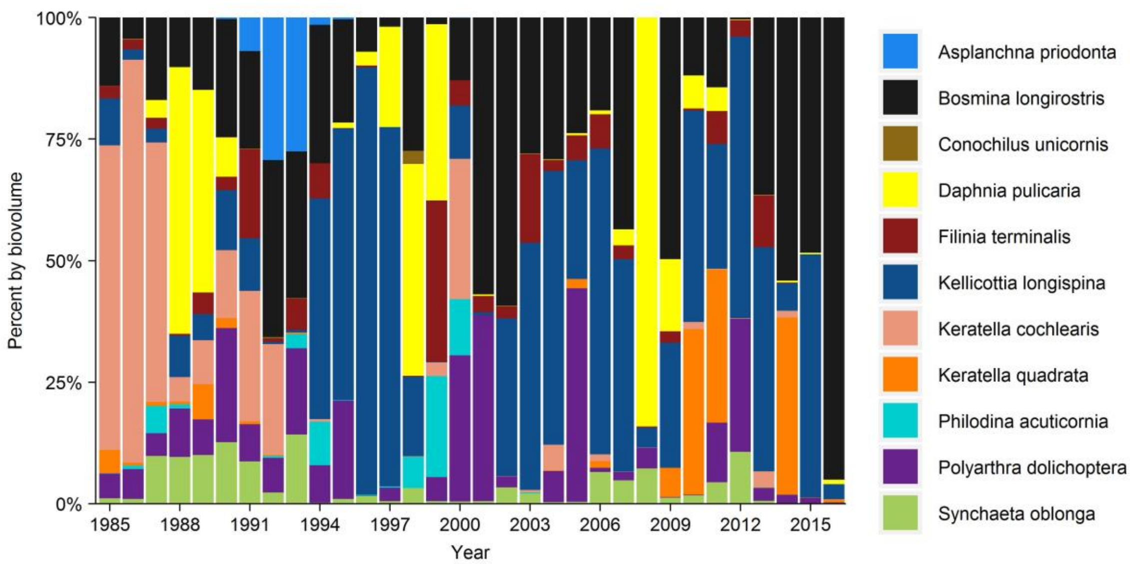


Figure 30. Long-term record of zooplankton assemblages in summer in Crater Lake.

8.5 Impact of Fish on Zooplankton (since 1986)

Daphnia is the Crater Lake's largest zooplankter (~2 mm long) and its abundance through time is strongly controlled by predation from kokanee salmon (*Oncorhynchus nerka*; landlocked Sockeye salmon). Kokanee are primarily plankton feeders that were introduced to the lake in the early 1900's. In Crater Lake, kokanee show a distinct "boom and bust" pattern where they experience wide fluctuations in density, weight, and maturity. The lake monitoring program has recorded three kokanee "boom and bust" cycles with a full sequence taking 9-10 years. When kokanee density (Figure 31A; black) is high, the fish literally "eat themselves out of house and home" and nearly all of the *Daphnia* (Figure 31A; orange) disappear from the water column. The kokanee population then slowly declines due to food scarcity with few if any fish reaching sexual maturity (Figure 31C). After 6-7 years of declining fish density, food resources recover and the remaining fish attain large size (Figure 31B), which leads to successful spawning and a rapid rise in density – continuing the cycle.

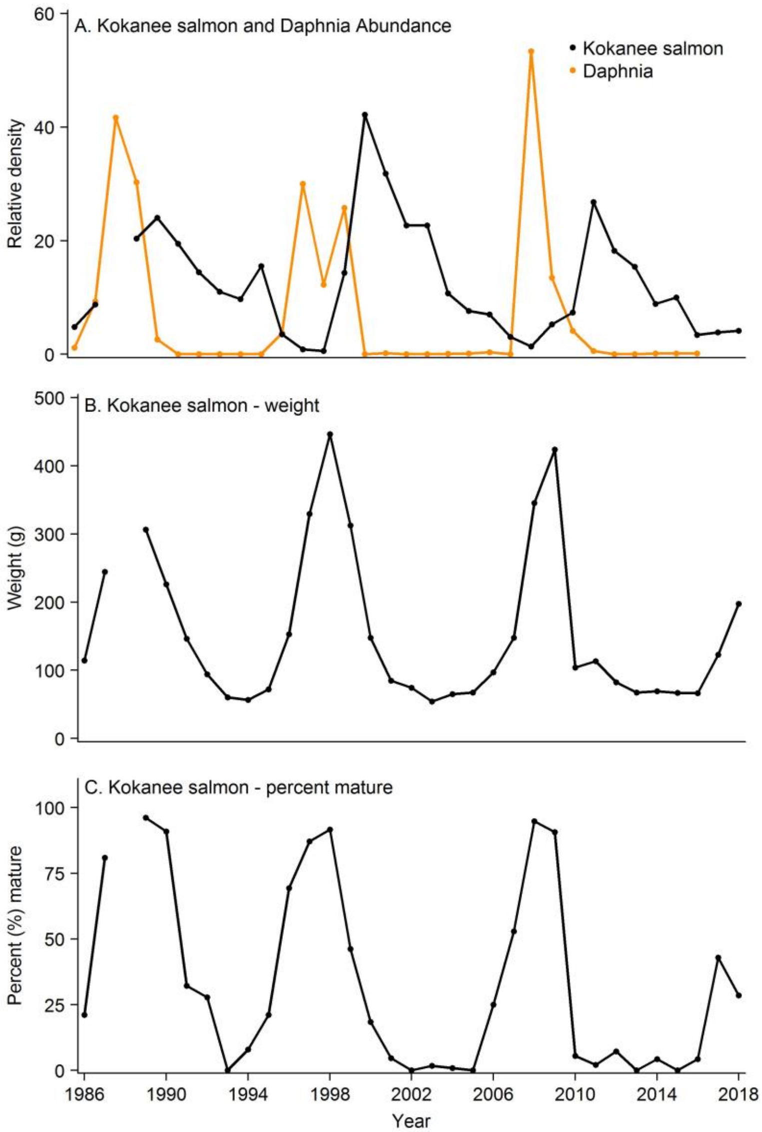


Figure 31. Long-term record of population dynamics of kokanee salmon and their main food source, *Daphnia*, including (A) abundance, (B) weight, and (C) percent of the population that is mature.

Daphnia represent the main food source for kokanee salmon in Crater Lake and as a result, follow a similar "boom and bust" population abundance cycle (Photo: Paul Hebert).

8.6 Native Newts and Invasive Crayfish (since 2008)

Mazama newts (*Taricha granulosa mazamae*) are endemic to Crater Lake and are a proposed subspecies of the more widely distributed rough-skinned newt (*T. granulosa*). Given a high degree of morphological, physiological, and genetic differentiation, Mazama newts appear to have been functionally isolated within the caldera for many generations. Park naturalists described their distribution as common along the shoreline as recent as the mid-20th century, but a systematic lake-wide survey in 2008 indicated that the spatial distribution of newts had substantially declined relative to historic records. At the same time, newts appeared to be supplanted by non-native signal crayfish (*Pacifastacus leniusculus*).

Crayfish were introduced to Crater Lake in 1915 as food for nonnative trout and salmon, which were introduced in the late 1800s. The results of a 2008 survey indicated that crayfish occupied habitat in 50% of the shoreline (Figure 32). Newts remained in areas that crayfish had yet to invade, but were virtually absent from areas occupied by crayfish. Annual surveys have been repeated at 40 locations along the shoreline and have recorded the continued expansion of crayfish distribution and concurrent decline in newts. In 2018, surveys showed crayfish occupied 80% of the shoreline, whereas newts had been reduced to about 30%. Studies have suggested several mechanisms for the elimination of newts by crayfish including predation, competition for food and cover, higher newt energy demands, and exposure to ultraviolet radiation.

Endemic Mazama newt and introduced signal crayfish compete for habitat in Crater Lake (NPS photos).

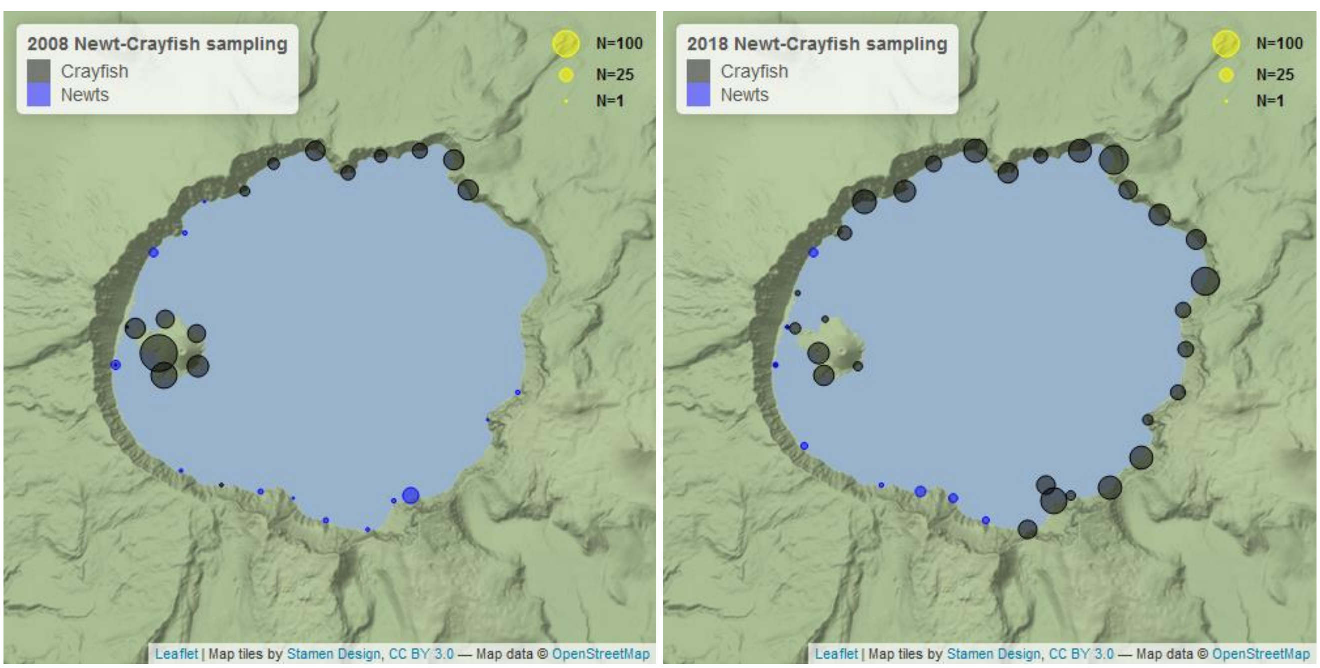


Figure 32. Survey results for newts and crayfish along the shoreline of Crater Lake in 2008 and 2018. Circle size is relative to abundance.

8.7 Horizontal movement of Crayfish (since 2014)

One question about crayfish is how fast they spread around Crater Lake. Annual sampling of the 40 survey sites suggest movement along the shoreline of approximately 600-1300 meters per year. However, it is difficult to observe small scale movements because of the course distance (1000 m) between the 40 locations that make up the standard lake-wide survey. In response, a special movement study was initiated in 2014. Sampling sites were setup every 50 meters (164 feet) beginning near the edge of the current distribution on the south-east side of the lake near Phantom Ship (Figure 33). These sites were sampled annually.

In 2011, crayfish were observed at low density on the caldera wall immediately adjacent to phantom ship. They remained at low density for several years, but increased dramatically in 2015. Similar patterns were observed at locations south-west of this location. It appears that horizontal movement of crayfish into new areas occurs in pulses. The movement is initiated by a few adult crayfish moving along the shoreline near the surface of the lake into an unoccupied area. These crayfish eventually reproduce leading to a large increase in density.

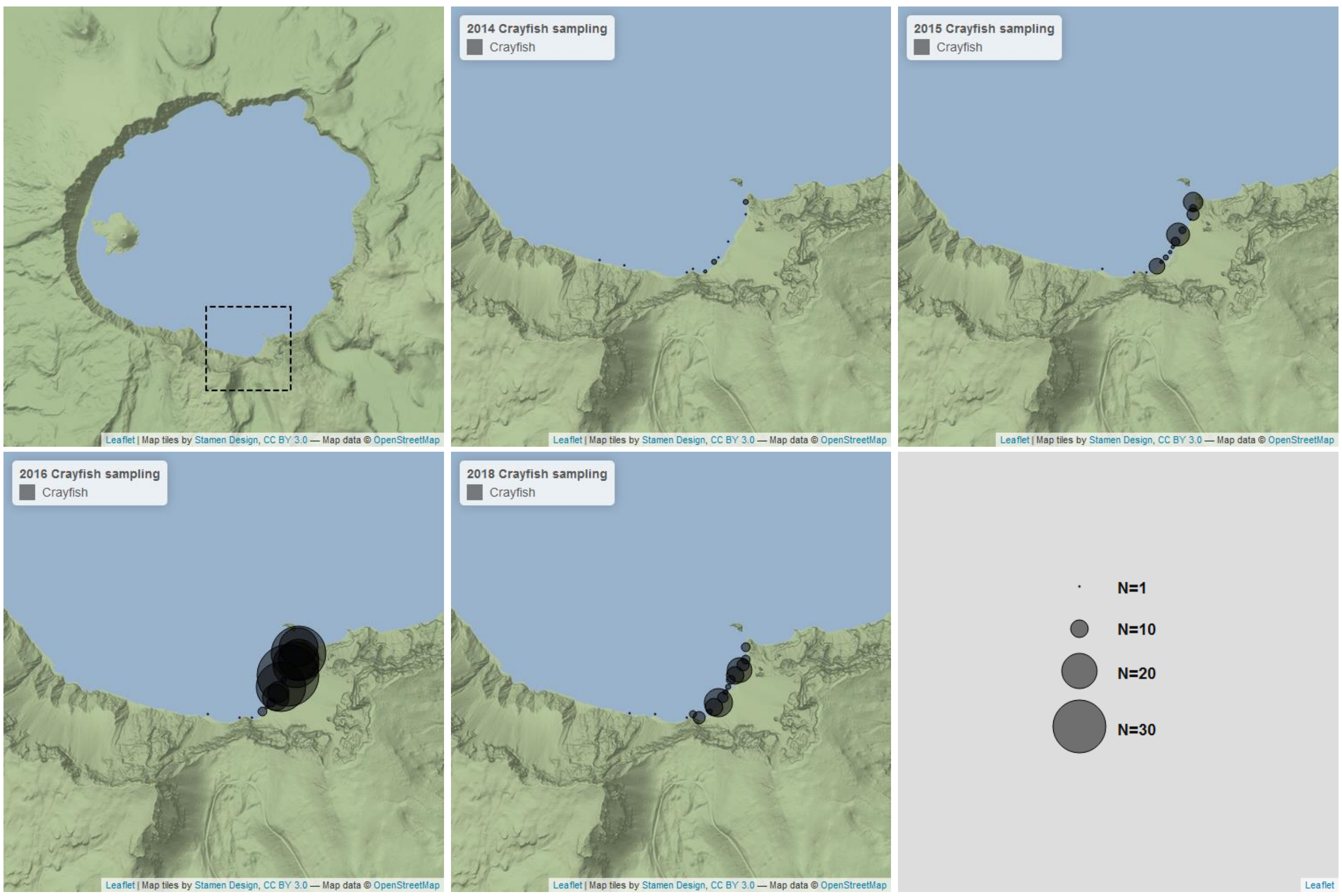


Figure 33. Survey results for crayfish movement along the shoreline of Crater lake 2014-2018. Circle size is relative to abundance.

8.8 Vertical movement of Crayfish

One method suggested to control crayfish movement and spread is placement of metal barriers that act as fences. Installation by SCUBA divers could only occur down to approximately 30 meters (100 ft) due to diver limitations at high elevation. Because crayfish in Crater Lake are known to occur down to 250 meters (820 ft), it is possible that crayfish would be able to bypass the barriers by crawling around the bottom. However, little is known about vertical movement of crayfish up and down the walls of the lake over short time periods. As a result, a mark-recapture study was initiated to assess their vertical movements.

The study involved marking crayfish and then tracking movement of these crayfish over the entire summer. A total of 305 crayfish were collected at 50 meters in Cleetwood Cove and individually tagged on the underside of their tails with a bright colored elastomer. Crayfish were immediately returned to the lake bottom at 50 meters depth. In September, the bottom of the lake from shoreline to 250 meters was sampled with crayfish traps spaced every 10 to 25 meters.

Overall, 7 of 305 crayfish (2.3%) were recaptured. One crayfish moved to deeper water (90 m), while the reaming recaptures moved shallower – two crayfish were caught at 30 meters, and five crayfish moved all the way up to the shoreline (1 m). Such large vertical movements by crayfish over a short timeframe suggests that installation of crayfish "fences" would likely not be effective in stopping crayfish movements around the lake.

Crayfish being marked with colored elastomer as part of a vertical movement study at Crater Lake (NPS photos).

8.9 Why are Crayfish more abundant now?

Park scientists have annually inspected Cleetwood Cove boat moorings for three decades via SCUBA diving and have noted a visual increase in crayfish density. Likewise, crayfish were introduced to Crater Lake more than 100 years ago (1915), yet only now are they poised to spread completely around the lake. So why might crayfish be more abundant now? Data from detailed monitoring of crayfish density that began in 2008, along with long-term monitoring of air and water temperature suggests warmer winters may be the culprit.

Crayfish density in summer tends to be lower following winters that are especially cold (Figure 34). In other words, crayfish density was positively correlated with winter water temperature. Studies of introduced signal crayfish in one of Sweden's largest lakes showed similar findings, with higher winter mortality attributed to colder water temperatures. Comparison of average winter air temperatures show that, during the study period (2008-present), temperatures have been above the long-term average (-7.4 °C). Specifically, 73% (8/11) of average winter air temperatures have been above normal, whereas 46% (39/73) were above average in the period leading up to the surveys (1931-2007). If especially cold winters result in high crayfish mortality, the warmer air temperatures over the last two decades may have allowed crayfish abundance to increase. At the same time, higher density may have forced more crayfish to move laterally around the shoreline in order to avoid competition.

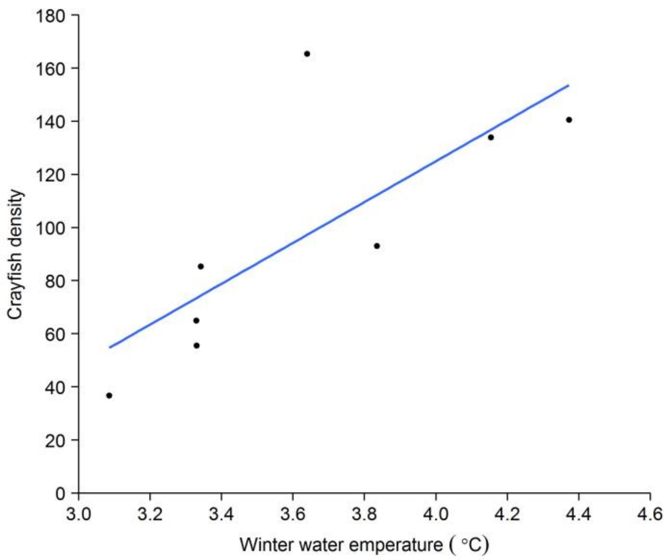


Figure 34. Crayfish density in summer and average surface water temperature in winter.

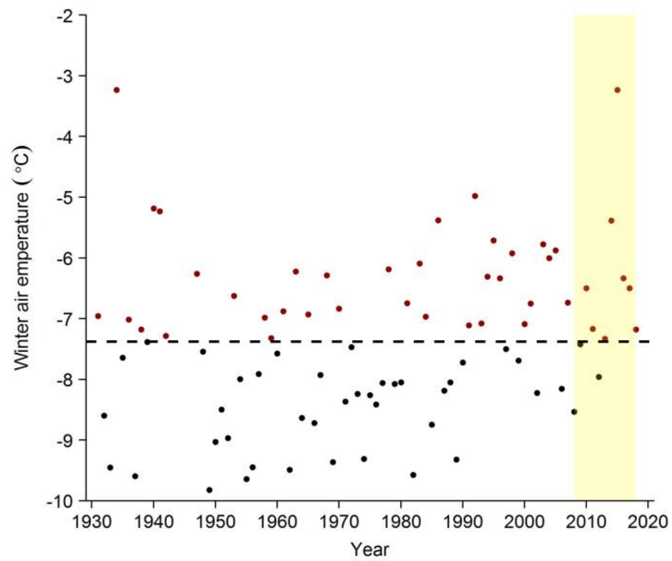


Figure 35. Average winter air temperature measured at Park HQ from 1931-2018. Yellow box highlights the time period of crayfish surveys. Red circles indicated temperatures above the long-term average (dashed line).

Researchers use SCUBA diving to survey for crayfish at deeper depths in Crater Lake (NPS photos).

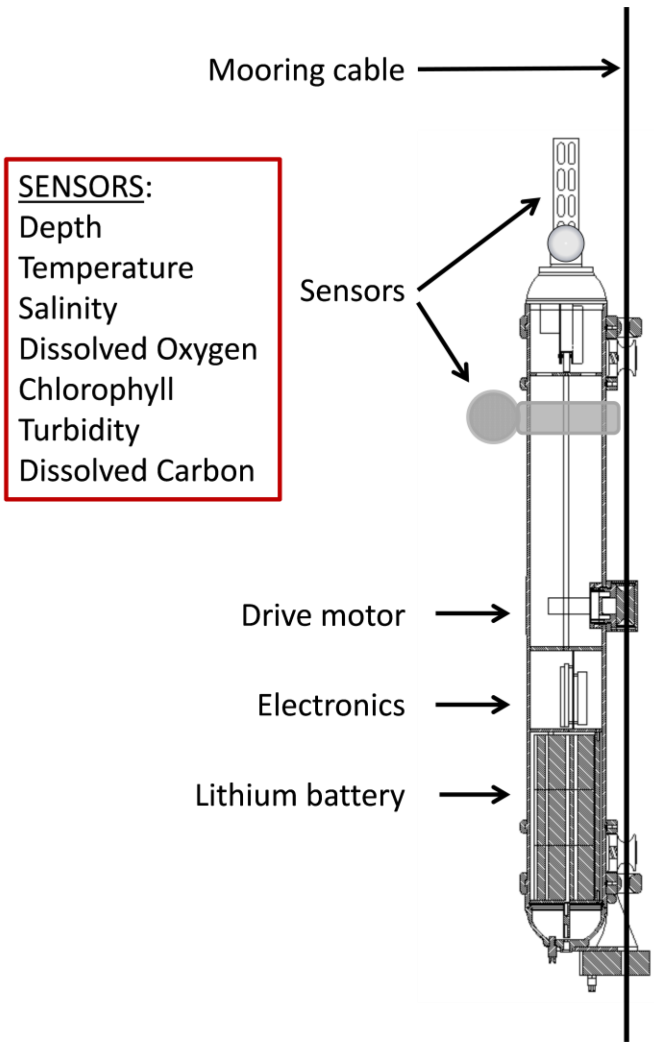
9.0 Year-round Lake Monitoring

9.1 Profiling Instrument (since 2013)

Crater Lake's monitoring program has long recognized that observing the lake during non-summer periods is crucial for understanding the overall health and function of the lake system because important physical, chemical, and biological processes occur during these times. However, weather conditions at Crater Lake make it extremely difficult for boat-based access to the lake in the fall, winter, and spring. Beginning in July 2013, year-round monitoring of the water column started, using a state-of-the-art profiling instrument [Ice-Tethered Profiler (ITP), McLane Labs, Falmouth, MA].

Woods Hole Oceanographic Institute initially designed the ITP instrument for studying ocean conditions under the floating Arctic ice-pack. There, the instrument is deployed through an 11" ice-auger hole and placed on a wire mooring hanging below the ice-pack. In Crater Lake, the instrument crawls up and down a wire mooring anchored to the bottom of the lake that is kept upright with floats near the surface. The ITP instrument travels up and down a wire mooring in the middle of the lake once per day and provides high resolution (1 m) data on chlorophyll concentration, particle density (i.e., water clarity), dissolved oxygen, dissolved organic matter, temperature, and salinity.

See section 9.2 to find out what we have learned about the lake in seasons other than summer.



Schematic of the ITP instrument in Crater Lake.

Recovering the ITP instrument from its 580 m long wire mooring line after spending an entire year in Crater Lake (NPS photo).

9.2 Profiler: Chlorophyll Results (since 2013)

Chlorophyll concentration is an important biological property of lakes and it is one of serval properties that the ITP profiler monitors. The data collected by the profiler permits in-depth observation of how chlorophyll changes over time, both within a single year and between multiple years. Two concepts the monitoring programs tracks are the establishment of a deep chlorophyll maximum (DCM) in summer and algal growth during winter-spring mixing events.

Figure 34 displays annual chlorophyll concentration down to 300 m over the course of four years. The establishment of a DCM in summer and subsequent shallowing throughout fall is a reoccurring pattern in Crater Lake. The presence of a DCM is a characteristic common to unproductive lakes and ocean systems and the vertical location of the DCM is a sensitive indicator of overlying water conditions. When interpreting long-term chlorophyll data that is collected on a less-frequent, monthly basis, it is critical to understand that DCM depth shallows over summer and timing in the onset of stratification is going to drive when that process begins.

As stratification breaks down and vertical mixing deepens, the DCM is eventually eroded and mixed away. A subsequent bloom of algae occurs throughout the mixed layer during the winter-spring period. Prior to the data provided by the ITP profiler, the monitoring program had only sampled the lake during spring mixing once in 1989. Variability in the duration and depth of a spring bloom may affect the availability of nutrients and clarity of the water during summer. Moreover, the amount of algae growing within the mixed layer and the depth to with mixing reaches, prior to the onset of summer stratification, may be important in determining the amount of nutrients that make it to the deep lake for long-term storage.

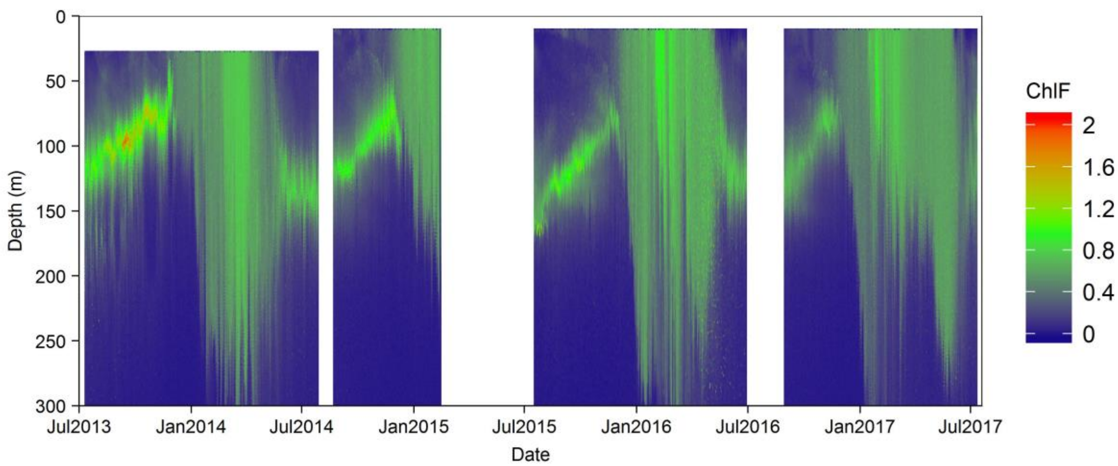


Figure 36. Daily measurements of chlorophyll fluorescence throughout the water column in Crater Lake, collected by an autonomous profiling instrument. White spaces represent missing data.

9.3 Profiler: Particle Density Results (since 2013)

Similar to chlorophyll, particle density is a measure of algal abundance, but it is based on scattering of light by algal particles, whereas chlorophyll is a measure of how "green" the water is due to algae. Figure 35 is similar to Figure 34, but shows annual particle density down to 300 m over the course of four years.

Particle density shows patterns similar to chlorophyll concentration with a few important differences. Unlike chlorophyll, particle density captures the concentration of algae living in the warm water floating on the surface during the summer. Chlorophyll is not accurate near the surface in the summer because chlorophyll within algae are muted by the extremely bright sun light. The opposite occurs at extremely deep depths where algal cells greatly increase chlorophyll levels because light levels are very low. These changes in chlorophyll at the cellular level are referred to as "photoacclimation" and are extremely important to quantify because they greatly affect the accuracy of chlorophyll as a measure of algae. Particle density, on the other hand, is a more accurate measure of algal biomass, especially when considering water clarity near the surface.

Clarity at the surface tends to be lowest in the fall, especially when deepening of the thermocline erodes the deep algal group and re-suspends the particles up to the surface. During winter and spring when the lake is mixing to great depth, particle density increases throughout the layer that is mixing. These year-round data show that total biomass of algae in the lake during the winter and spring can actually be higher than during summer. We suspect that the amount of algae that grow in the winter and the depth of mixing prior to the onset of stratification may drive how much nutrients end up making it into deep-water storage in any given year.

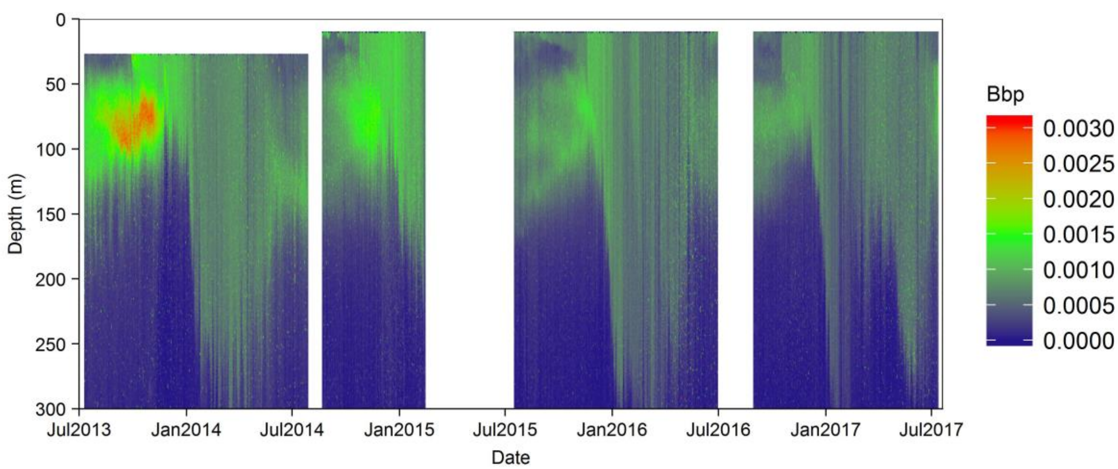


Figure 37. Daily measurements of particle density throughout the water column in Crater Lake, collected by an autonomous profiling instrument. White spaces represent missing data.

Hauling gear back up the trail with tractor and trailer

Researchers from University Nevada Reno and Lake Tahoe

Repairing a deep-water mooring on a windy afternoon

Collecting fish using gillnets

Collecting benthic insects with a battery powered vacuum

Giving a school group a tour of the research boat

National Park Service
U.S. Department of the Interior

[Crater Lake National Park](#)
P.O. Box 7, Hwy. 62
Crater Lake, OR 97604