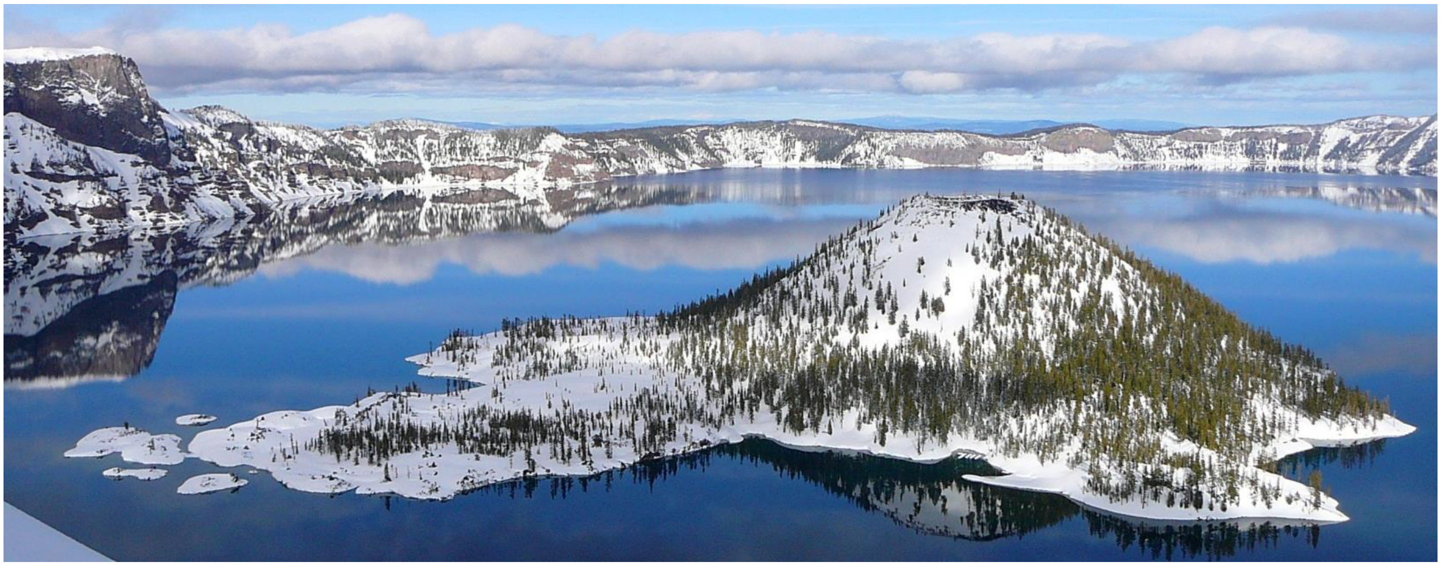
# Crater lake Long-Term Limnological Monitoring Program

# STATE OF THE LAKE REPORT
# 2014



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**National Park Service**
**Crater Lake National Park, Oregon**

**Cover**: Crater Lake in winter looking northeast across the lake.
Photograph by Dave Grimes

## Contents

# 1. EXECUTIVE SUMMARY

The National Park Service operates a long-term limnological monitoring program at Crater Lake to ensure the health and resource preservation of this special aquatic system. The program serves as both a monitoring and research platform to develop and communicate to park management, the science community, and the public a better understanding of the biological, physical, geochemical and climatological processes within and effecting the lake. Protected natural areas like Crater Lake National Park play a key role in answering important questions in ecosystem and earth sciences. In particular, Crater Lake is an ideal case-study for climate change because it's isolation from agricultural, industrial, and landscape level impacts, small watershed, and protected status, make climate change the likely largest external source of long-term alterations.

This State of the Lake Report provides updated trends in climate and lake characteristics through 2014 and presents our current state of knowledge of this remarkable lake ecosystem including its special optical properties, thermal and biological characteristics, deep-water mixing processes, interaction with the surrounding climate, as well as updates of more recent studies on introduced species and year-round remote sampling. This report is primarily intended to inform non-scientists about variables affecting the health of Crater Lake. It is not intended as an exhaustive review of all pertinent limnological literature but does present examples from other lake and climatological studies where appropriate. For a more detailed scientific review, please see the January 2007 Hydrobiologia Journal special issue on the Crater Lake limnological program. (http://link.springer.com/journal/10750/574/1/page/1)

View of Crater Lake from Wizard Island (NPS photo)

Crater Lake is one of the clearest lakes in the world and is widely known for its stunning deep-blue color. Concern that the remarkable clarity and color of Crater Lake may be declining was the 1982 impetus for initiating lake studies and long-term monitoring. The trend analyses included in this report reaffirm that Crater Lake does not show a reduction in water clarity over the time period measured. Moreover, both Secchi disk clarity and depth of light penetration may indicate a slight increase in clarity over the last 35-37 years. The long-term data also shows that clarity can be highly variable from year to year, likely driven by various factors, such as winter lake mixing, timing of thermal stratification, thermocline depth, sediment from rain events, and the production of phytoplankton. In particular, the presence or absence of deep-water mixing in the winter, and the corresponding upward flux of nutrients and production of phytoplankton, are dominant drivers of near-surface clarity in the summer.

The most significant trends we have documented to date in the Crater Lake ecosystem involve warming climate and the corresponding impact on lake thermal structure. An increase in summer air temperature appears to have affected three fundamental thermal properties of the lake;1) an increase in summer surface water temperature by 2.8°C (5°F) since 1965, 2) earlier onset of stratification in the spring by 24 days, and 3) a 53% reduction in the average thickness of the thermocline (warm water floating on the surface in summer). Trends in these fundamental thermal properties are critical to recognize and appreciate because they effect many other lake 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.

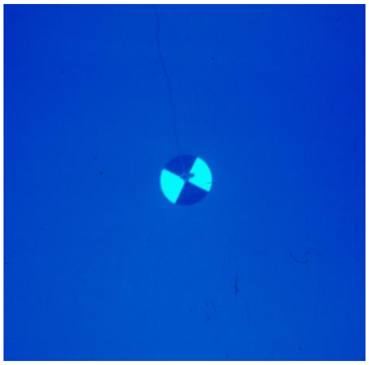
Unlike the thermal properties that indicate significant trends through time, few of the biological variables show significant uni-directional changes but many show significant annual variability or cyclic change. Crater Lake's extremely low productivity of algae is somewhat variable but consistent through time. Introduced fish abundance cycles approximately every 10-yrs from very low to relatively high abundance (up to 24 orders of magnitude). The monitoring data indicate that kokanee salmon predation controls *Daphnia* abundance, the lakes largest zooplankton, whose abundance cycles with fish density. Introduced crayfish are expanding rapidly in abundance and distribution and are having serious impacts on native taxa. Recent collaborative studies with University Nevada Reno and US Geological Survey have focused on introduced crayfish, and the impact of crayfish on endemic salamanders, in particular the rough skinned newt, and bottom dwelling insects. These studies have shown that newts in Crater Lake have been physically and genetically isolated such that they are now distinct from newts outside the caldera and have been proposed as a distinct sub-species. Crayfish are displacing the native Crater Lake newt. Crayfish have spread to nearly 80% of the lake shoreline while newts have disappeared from most of these same areas. Studies conducted at Crater Lake indicate multiple replacement mechanisms may be at work, including direct predation by crayfish and introduced trout, crayfish avoidance by newts, competition for food and cover, and indirectly increasing newt energy demands and exposure to ultraviolet radiation. Continued increases in crayfish distribution and abundance will likely lead to further declines in newt abundance and distribution, and perhaps elimination of the Crater Lake newt.

The monitoring program has long recognized that studying Crater Lake during fall, winter, and spring is crucial for understanding the health and functioning of the lake system. However, extreme weather conditions prevent routine lake access outside of summer. An innovative, state-of-the-art profiling instrument has recently been added to the monitoring program and has successfully collected the first year-round data. The instrument provides unprecedented detail both vertically within the water column (every 1-2 m) and over short time scales (daily) that are simply not feasible with traditional boat-based sampling. Just as important, it provides our first detailed view of biological conditions and various physical and biological processes during non-summer periods.

The long-term monitoring program is a collective effort by many scientists, managers, summer technicians, and students. We are particularly indebted to 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 advancing our current understanding of Crater Lake and integration of monitoring technology. In particular, Robert Collier, Jack Diamond, Chris Moser, Jim McManus, and Greg Crawford. The present monitoring program is funded by Crater Lake National Park.

Recovering sediment trap mooring with Oregon State University personnel

## 2. PROGRAM OVERVIEW



Secchi disk in Crater Lake.

Limnological studies of Crater Lake between 1896 and 1970 were sparse, fragmented, and sampling methods were often not comparable. Enough was known about the lake from these studies, however, to indicate that this deep lake was extremely clear, low in nitrogen, slightly alkaline, thermally stratified in summer, well oxygenated throughout the water column, low in primary production, and contained low densities of phytoplankton, zooplankton and introduced fish. Limnological studies conducted from 1978 to 1981 suggested that the water quality of the lake might have deteriorated because the clarity of the lake had decreased compared to observations made years earlier. A panel of limnologists reviewed the available lake data in 1982 and concluded that the database was insufficient to determine if the lake had actually changed. One of the recommendations of the review panel was to monitor and document the basic characteristics of the lake. Congress passed Public Law 97–250 in the fall of 1982 that directed the Secretary of the Interior to conduct a 10-year study to examine the lake for possible deterioration of water quality.

The main goals of the National Park Service limnological program at Crater Lake were to: (1) develop a reliable database for use in the future; (2) develop a better understanding of physical, chemical, and biological characteristics and processes of the lake; (3) establish a long-term monitoring program; and (4) investigate the possibility of long-term changes; and (5) if changes were found and related to human activities, identify the cause(s) and recommend ways of mitigating the change(s).

The first field season was conducted during the summer of 1983, although the National Park Service sampled the lake in the summer of 1982. The final report 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. Recognizing the complexity identified during the 10-year program, Park Superintendent Robert Benton emphasized the need for long-term monitoring to understand the dynamics of the lake. His vision was realized by 1994 when the National Park Service provided base funding to continue the lake monitoring program indefinitely.

The purposes of this report are two-fold: 1) to present results of long-term change analyses through 2014 and 2) to update the state of our knowledge and understanding of the Crater Lake ecosystem and impact of the surrounding climate. This report is primarily intended to inform non-scientists about variables affecting the health of Crater Lake. Most of the Crater Lake limnological monitoring datasets are now of sufficient duration (25+ years) that longer-term trends can be evaluated. 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.

*Biological, physical, chemical, and climatological monitoring parameters.*

| Biological | Physical | Chemical | Climatological |
|---|---|---|---|
| Chlorophyll | Secchi clarity | Nutrients | Wind speed and direction |
| Primary productivity | Light penetration | Dissolved oxygen | Air temperature |
| Particle density | Water temperature | Alkalinity | Relative Humidity |
| Phytoplankton | Lake level | pH | Snow depth |
| Zooplankton | Thermocline depth | Conductivity | Precipitation |
| Fish | Stratification date | Trace elements | |

# 3. LIMNOLOGICAL OVERVIEW

Crater Lake is located within Crater Lake National Park 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 and collapse of the volcano Mount Mazama. The caldera that formed was roughly 1220 m (4000 ft) deep and 10 km (6 mi) across and filled approximately half-way up with water. The lake has a maximum depth of 594 m (1949 ft) relative to a surface elevation of 1883 m (6178 ft), making it the deepest lake in the United States and 8th deepest in the world. It has a mean depth of 350 m (1148 ft) and a surface area of 53.2 km$^2$ (20.5 mi$^2$). The shoreline is 31 km (19.3 mi) in length and the lake is nearly circular with the diameter ranging between 8 km and 10 km (5 to 6 mi). There is no surface outlet and the surface inlets are limited to small springs draining the steep caldera walls. Unlike other Cascade Mountain lakes, Crater Lake rarely freezes over in the winter due to the heat content of the enormous water volume. The area receives 165 cm (65 in) of total precipitation annually on average, the majority falling as snow during winter.

Crater Lake is widely known for its extremely clear water and deep blue color. Secchi depth during summer typically ranges between 25 and 35 m (82 to 115 ft). Limnologically, Crater Lake is a large dimictic lake with periods of partial vertical mixing in fall and spring, strong thermal stratification in the summer and reverse stratification in winter. During mixing periods, the lake routinely circulates to a depth of 200 to 250 m due to wind and convective cooling. Mixing to the bottom does not occur every year but on average every 2-5 years through a process of thermobaric instability. Near-surface temperatures typically range from 2 to 3°C (36°F) in winter and up to 18°C (65°F) in summer. As near surface temperature increases in the late spring, a thermocline forms typically at a depth between 5 and 20 m (16 to 66 ft).

Crater Lake is extremely unproductive (ultra-oligotrophic) with peak chlorophyll concentration less than 2 µg/l. The remarkable clarity allows an astonishingly deep chlorophyll maximum in summer, typically in the 100-120 m (330-395 ft) range. Phytoplankton are extremely diverse with over 160 taxa identified. Zooplankton on the other hand are generally limited to 2 cladoceran and 10 rotifer taxa. Crater Lake was originally barren of fish but several salmonid species were introduced into the lake between 1888 and 1941. Self-sustaining populations of kokanee salmon and rainbow trout exist in the lake today. Crayfish were introduced to the lake in 1915 to feed the introduced fish. Very few aquatic macrophytes occur near the surface. However, a deep-water moss community exists between 26 and 140 m (85 to 460 ft). The moss hangs like ice-cycles on the near vertical caldera walls and forms thick fields on the gentler slopes around Wizard Island.

The lake water is slightly basic with an average pH of 7.5 and has a relatively high buffering capacity (total alkalinity > 25 mg/l) for a Cascade Mountain lake due to geothermal inputs. The lake is well oxygenated throughout the water column (>90% saturation) and nutrient concentrations are extremely low (nitrate< 0.025mg/l, phosphate< 0.02mg/l). The lake is primarily nitrate and iron limited. Most of the available nitrate is located deep in the lake below 200 m. Upward mixing of the deep-water nitrate pool from deep-water mixing in winter is estimated to account for more than 85% of the nitrogen transported to the upper water column.

The first research expedition was conducted off the vessel “Cleetwood” in 1886 (NPS photo)

## 4. 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 distinguish between the range of natural variability and cyclic changes, 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. 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.

## Statistical Trend Analyses

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 (5.4). Consistent with the increase in summer air temperature, summer surface water temperature (6.1), onset of stratification (6.3), and thermocline depth (6.6) all show significant trends. Two optical properties, Secchi disk clarity (8.1) and depth of light penetration (8.3), 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 (9.3). Other biological characteristics vary widely annually or cyclically (e.g fish and zooplankton), or were not part of the monitoring program when this report was written (e.g introduced crayfish which are increasing rapidly and the corresponding decline of the endemic Mazama Newt ).

*Summary of statistical trend analyses for monitoring variables*

| VARIABLE | YEARS | SEASON | P-VALUE | TREND | SLOPE | TEST |
|---|---|---|---|---|---|---|
| CLIMATE | | | | | | |
| Night air temperature | 1983-2014 | Winter | 0.76 | none | - | seasonal |
| Night air temperature | 1983-2014 | Spring | 0.47 | none | - | seasonal |
| Night air temperature | 1983-2014 | Summer | **0.003** | **warmer** | 0.049 | seasonal |
| Night air temperature | 1983-2014 | Fall | 0.33 | none | - | seasonal |
| April snowpack | 1935-2014 | annual | **0.046** | **lower** | -0.143 | Mann |
| OPTICAL | | | | | | |
| Secchi disk depth | 1978-2014 | Summer | **0.028** | **deeper** | 0.082 | seasonal |
| Particle density 0-30 m | 1988-2014 | Summer | 0.11 | none | - | seasonal |
| Depth of 1% light penetration | 1980-2014 | Summer | **0.053** | **deeper** | 0.48 | seasonal |
| THERMAL | | | | | | |
| Onset of stratification | 1966-2014 | annual | **0.01** | **earlier** | -0.5 | Mann |
| Thermocline depth | 1978-2014 | Summer | **<0.001** | **shallower** | -0.241 | seasonal |
| Surface water temperature | 1965-2014 | Summer | **0.05** | **warmer** | 0.054 | seasonal |
| 20 m water temperature | 1983-2014 | Summer | **<0.001** | **cooler** | -0.050 | seasonal |
| 100 m water temperature | 1983-2014 | Summer | 0.14 | none | - | seasonal |
| 300 m water temperature | 1988-2014 | Summer | 0.07 | none | - | seasonal |
| 500 m water temperature | 1988-2014 | Summer | **0.003** | **cooler** | -0.002 | seasonal |
| BIOLOGICAL | | | | | | |
| Chlorophyll 0-30 m | 1991-2014 | Summer | 0.28 | none | - | seasonal |
| Chlorophyll 40-180 m | 1991-2014 | Summer | 0.12 | none | - | seasonal |
| Primary productivity 0-30 m | 1987-2014 | Summer | 0.22 | none | - | seasonal |
| Primary productivity 40-180 m | 1987-2014 | Summer | 0.13 | none | - | seasonal |
| Particle density 0-30 m | 1988-2014 | Summer | 0.11 | none | - | seasonal |
| Particle density 31-200 m | 1988-2014 | Summer | **0.004** | **larger** | <0.001 | seasonal |

# 5. CLIMATE

## 5.1 Present and Future Air Temperature

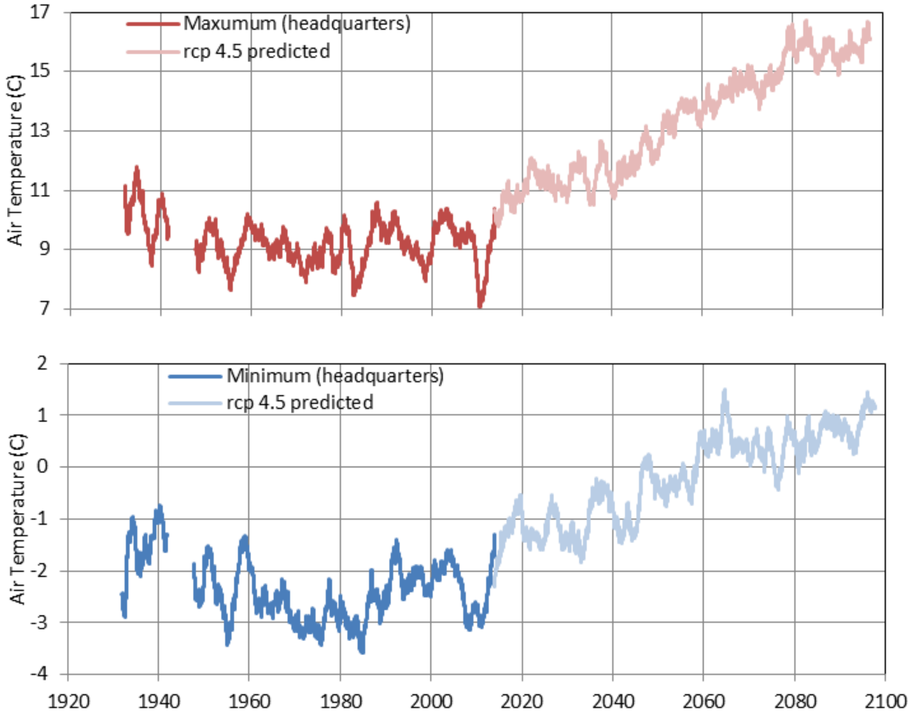
Since 1931

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.

The figure below 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 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 83 years.

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

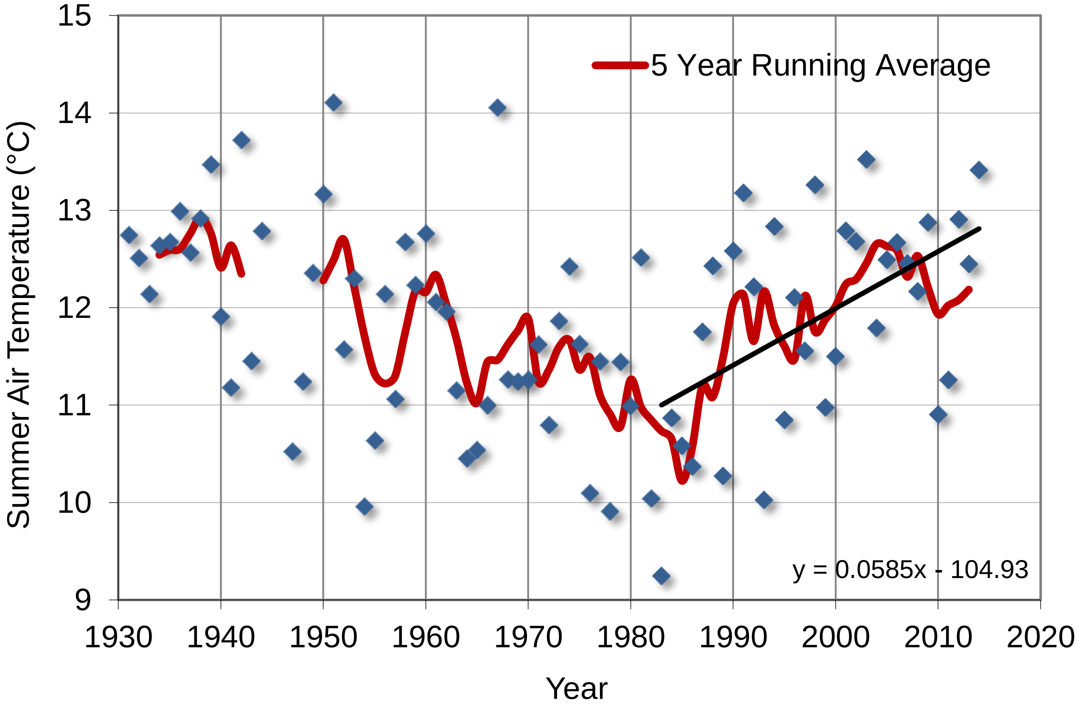


## 5.2 Summer Air Temperature

Since 1931

The long-term average summer (Jul-Sep) air temperature record from park headquarters shows a period of general decline from the 1930's through the mid 1970's, followed by a period of increasing temperature to present. This shift is in close agreement with other studies and is noted to be a widespread pattern across western North America.

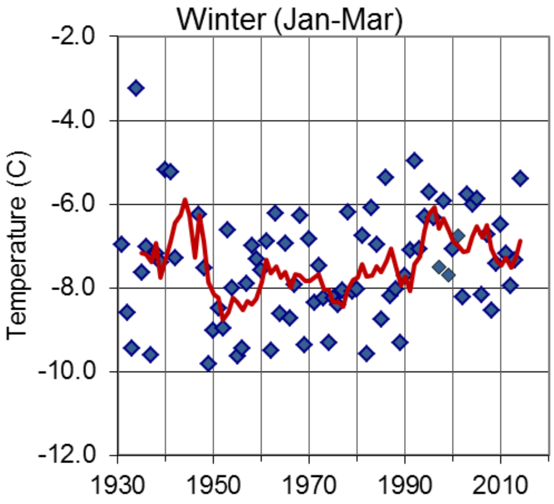
The overall increase in average summer temperature since the beginning of the lake monitoring program in 1983 was 1.9 °C (3.6 °F). Although the increasing trend since the 1980's was significant (p=0.003), these air temperatures were still within the range of previous variability recorded at Crater Lake during the first half of the twentieth century.

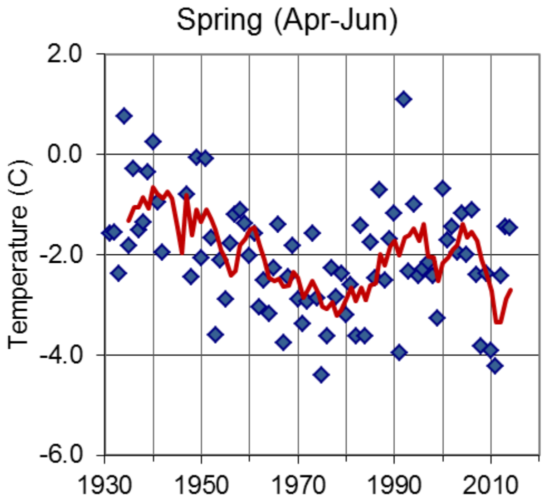


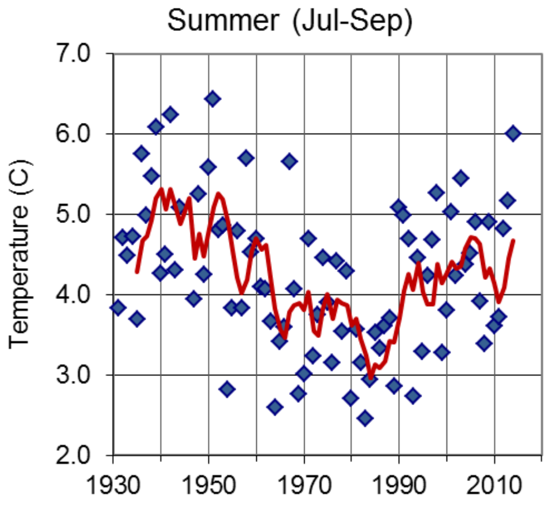
## 5.3 Air Temperature by Season

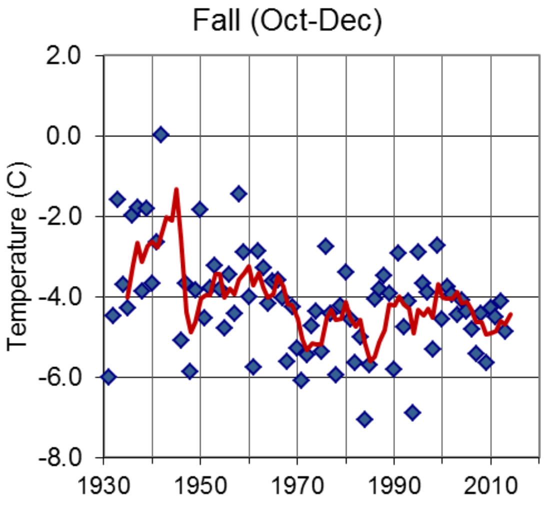
Since 1931

The long-term trends in nightly minimum air temperature at Crater Lake differ by season. Spring and summer seasons began to show increasing trends in temperature in the early 1980's. Winter has shown a period of general warming since the 1950's, whereas the temperatures in the fall have not shown a trend.







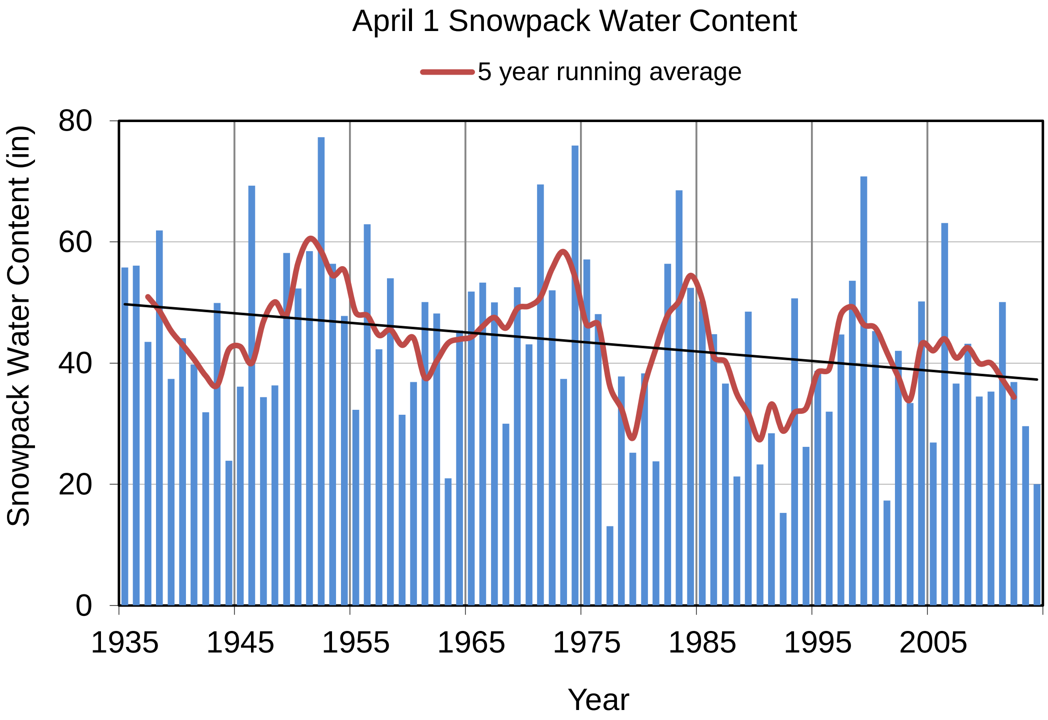


## 5.4 Snowpack

Since 1935

Many aspects of meteorology are highly variable from year-to-year, including snowfall. The long-term trend (since 1935) in snowpack water content at the beginning of April indicates a statistically significant decline (p=0.046) at an average rate of 1.4 inches (water equivalent) per decade. In terms of actual snow depth, this decline is about 3 inches per decade. This decrease in snow is similar to many mountain areas of the pacific-northwest.

Rim weather tower encrusted in snow (NPS photo)



# 6. THERMAL PROPERTIES

## 6.1 Summer Surface Water Temperature

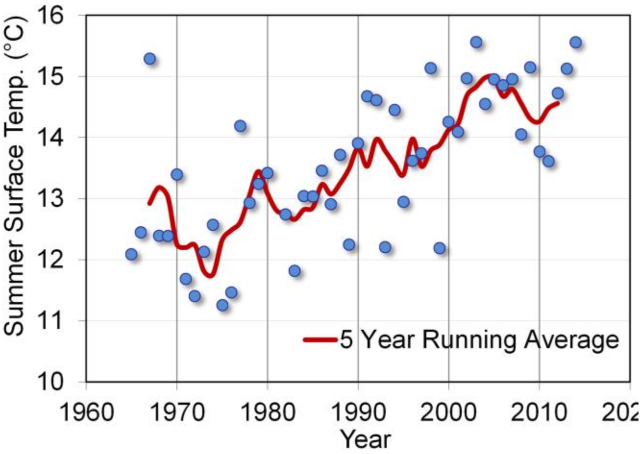
Since 1965

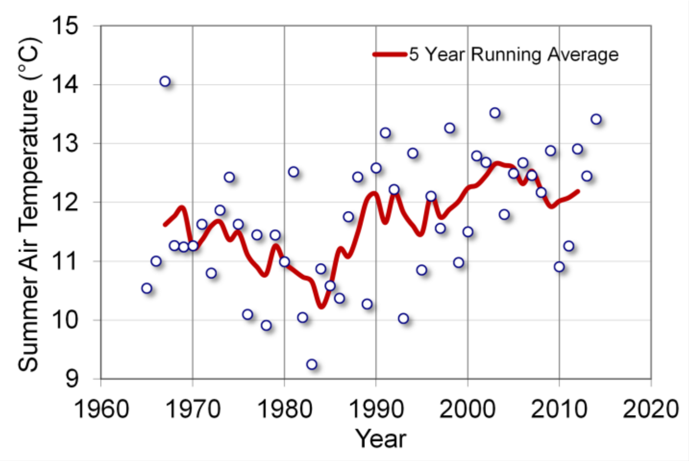
The temperature of the lake surface water during summer has increased by 2.8°C (5°F) since temperature records began in 1965. In the 25 years prior to 1990, only 2 years (8%) had mean summer surface temperature greater than 14°C. Since 1990, 68% (17 of 25) of the years were warmer than 14°C.

The increase in surface water temperature appears to be driven largely by an increase in air temperature. 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 the primary cause of increasing water temperature, or higher air temperature in concert with earlier onset of thermal stratification (Lake Superior), or changes in cloud cover.

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



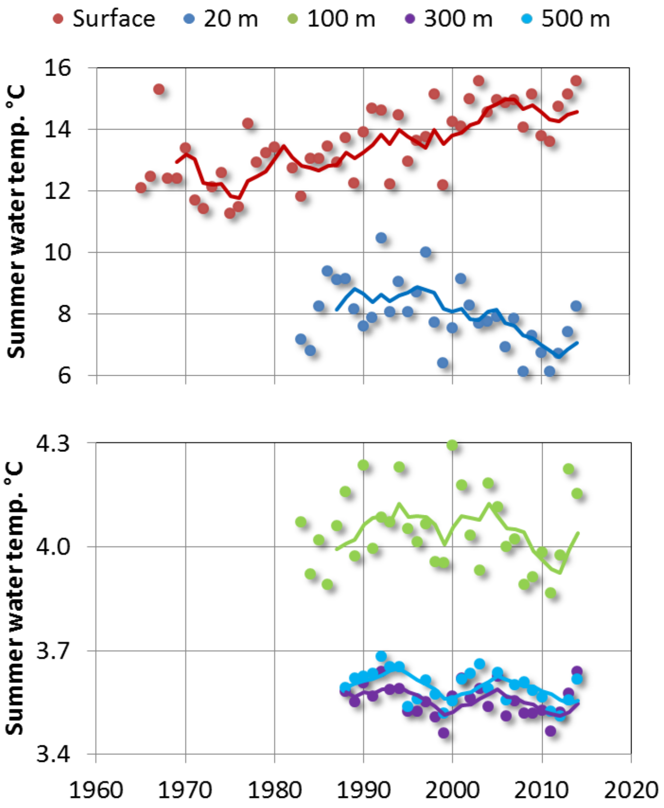


## 6.2 Summer Water Column Temperature

(Start date depth dependent)

Long-term trends in summer water temperature are markedly different depending on water depth within the lake. Surface water temperature shows a statistically significant increase since 1965 ($p=0.05$) which corresponds with increasing summer air temperature at Crater Lake (section 5.2). At 20 m depth the opposite trend is observed ($p<0.001$) (upper panel at right). The apparent cooling at 20 m depth is associated with the shallowing of the thermocline layer of warmer surface water. Because thermocline depth has been moving closer to the surface over the same period (section 6.6), the water at 20 m in recent years is now more characteristic of the deeper and colder water column than when the monitoring program began in the early 1980's. Water temperature below 100 m (lower panel at right) in the summer is much colder and does not show a statistically significant long-term trend or change. The temperature below 100 m is influenced by the depth of winter mixing of the water column.

The RV Neuston is the Park's primary vessel for monitoring and research activities (NPS photo)



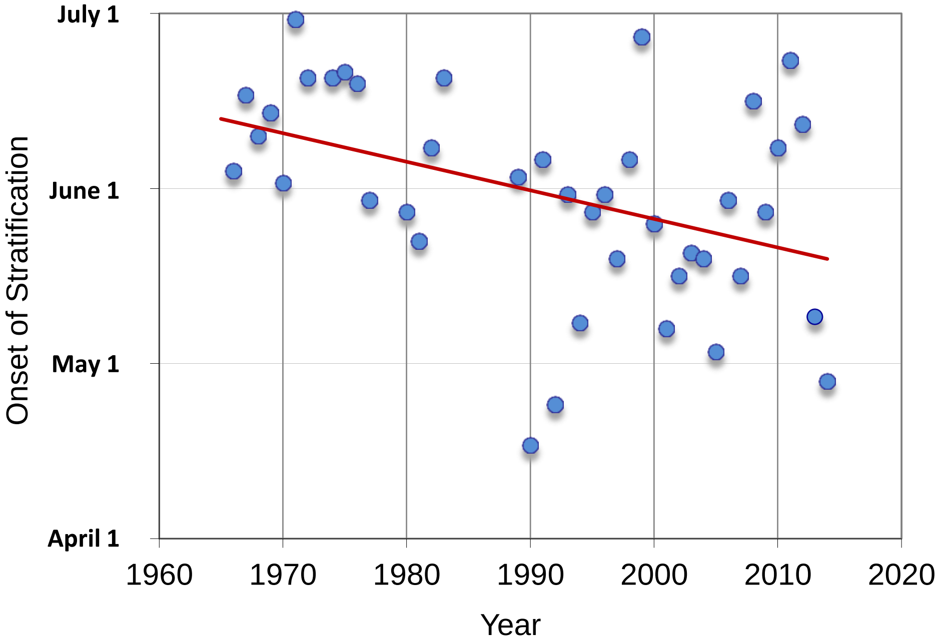
## 6.3 Onset of Summer Stratification

Since 1966

Summer thermal stratification is characterized by warmer water floating on the lake surface, over cooler water below. Warmer water floats on cooler water because it is less dense. The onset of stratification signifies the end of vertical mixing of the water column that occurs in the winter and spring. Ecologically, this change is important because stratification effectively separates the surface waters from the rest of the lake. Surface clarity in Crater Lake is typically clearest soon after the onset of stratification and prior to growth of shallow-water algal taxa near the surface. The cessation of vertical mixing also allows phytoplankton and zooplankton to stabilize and grow at discrete depths within the water column. Consequently, timing in the onset of stratification is important to biological, chemical, and physical processes in lakes.

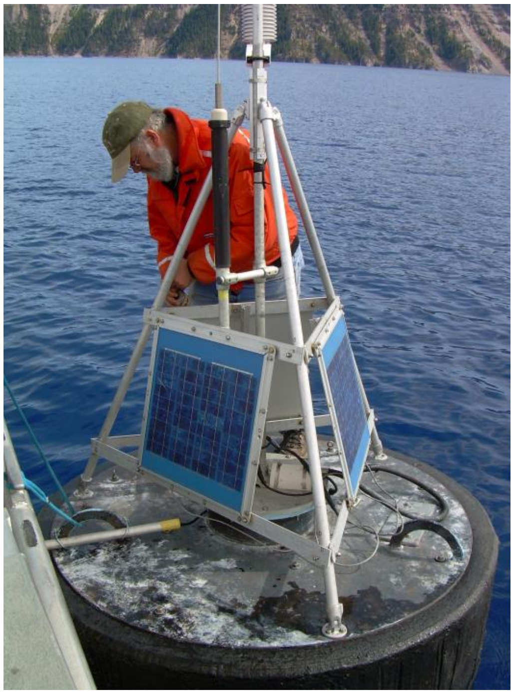
The beginning of the summer stratified period in Crater Lake occurs approximately 24 days earlier today than it did in 1966, albeit with considerable year to year variation. Prior to 1990, stratification began after June 1 75% of the time (12 of 16 years). After 1990, only 7 of 25 years (28%) began later than the 1st of June. The statistically significant long-term 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 on drivers of stratification onset.

The onset of stratification is defined here as the day of the year that surface temperature reaches and stays above 3.9 °C (39 °F) (the temperature of maximum density for water).

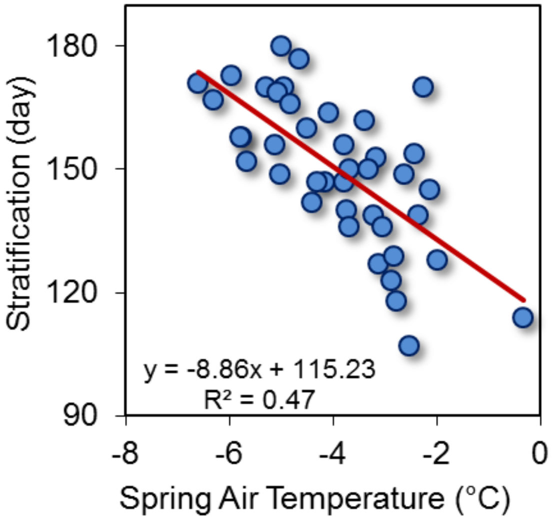


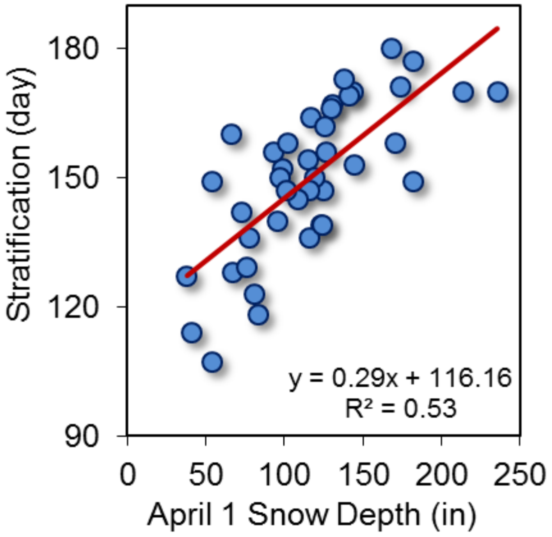
## 6.4 Drivers of Thermal Stratification Onset

The year to year variation in the onset of thermal stratification at 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 the variation in stratification date. Years with warmer spring air temperature tend to stratify earlier. Likewise, years with less snowpack in the spring stratify earlier. Snowmelt from the caldera walls during 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.



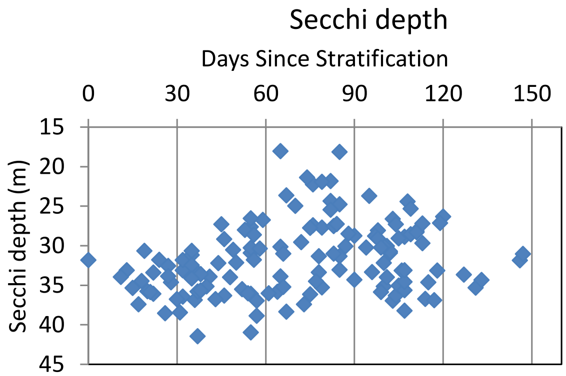
Dr. Robert Collier (Oregon State University) working on the floating weather buoy. The temperature sensor used for tracking the onset of stratification is located under the buoy at a depth of approximately 1 meter. (NPS photo)

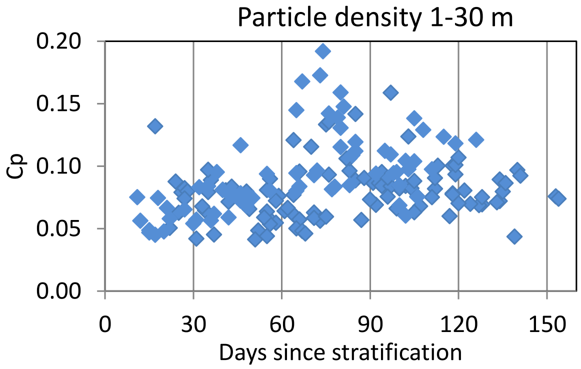


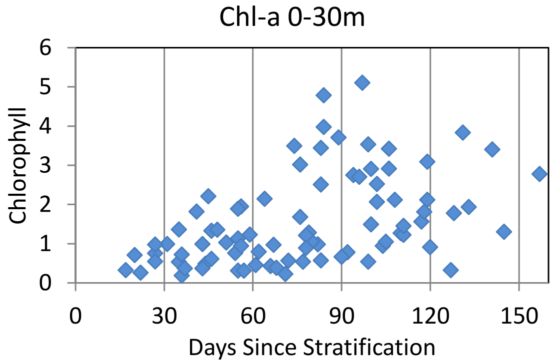


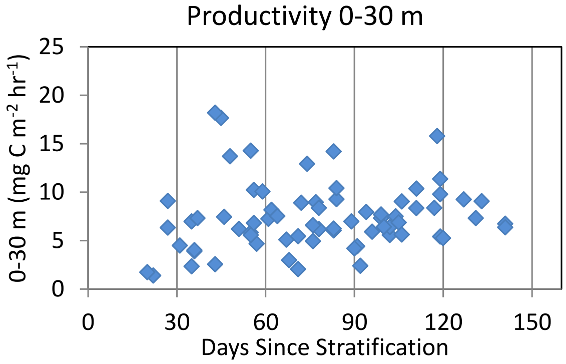
## 6.5 Impact of Stratification Onset

The onset of stratification appears to influence the timing of near-surface phytoplankton community development in the summer which directly influences Secchi disk water clarity. The figures at right plot Secchi disk depth, particle density, chlorophyll, and primary productivity in the top 30 m of the lake on the y-axis and the number of days since the onset of stratification on the x-axis. . The data suggest that water clarity tends to be highest and algae concentration lowest soon after the lake stratifies. The algae in the top 30 m tend to peak 60 to 90 days after the onset of stratification.









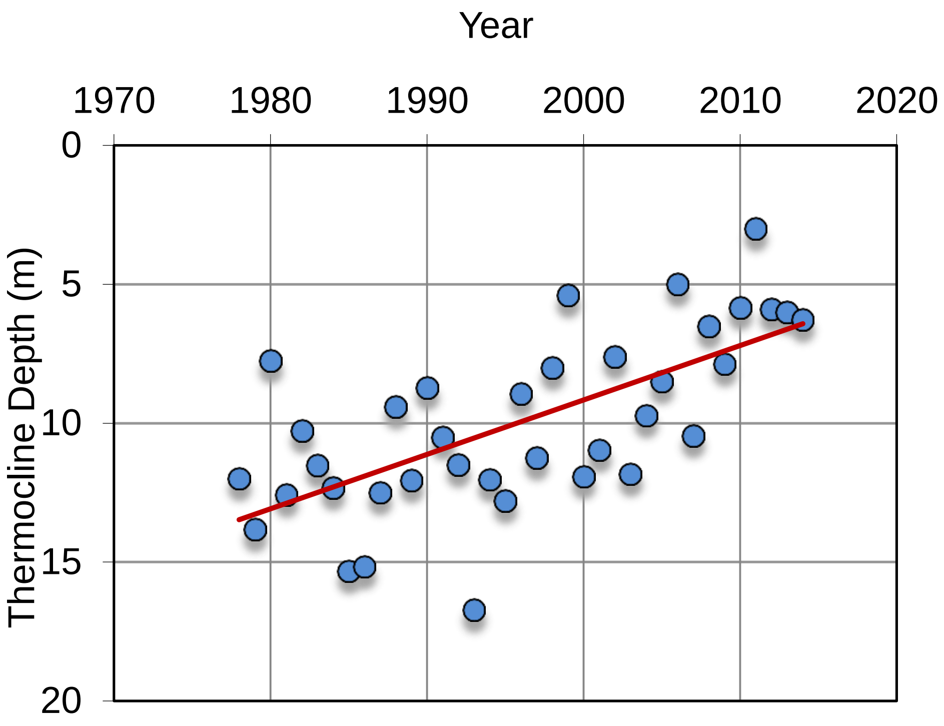
## 6.6 Summer Thermocline Depth

Since 1978

The thermocline is the depth of transition between the warmer water floating on the surface and the colder water below. Detailed temperature measurements within the Crater Lake water column have been collected since 1978. Over these 37 years, the thickness of the warm water floating on the surface has decreased by approximately 53%, moving closer to the surface of the lake by more than 7 m (23 feet). Similar trends in thermocline depth have been observed in other large lakes of North America, including Lake Huron, Lake Mendota, and October thermocline in Lake Tahoe.

The shallower thermocline depth in Crater Lake appears to be primarily driven by an increase in surface temperature, which has risen approximately 2.75°C (5°F) since 1965 (section 6.1). Higher water temperature at the surface of lakes tends to result in a shallower thermocline because warmer water is more buoyant (less dense) making it more difficult for wind to force the thermocline deeper into the lake.

The summer thermocline is defined as the depth of greatest temperature decrease per meter when descending.



# 7. MIXING PROCESSES

## 7.1 Episodic Deep-Water Winter Mixing Events

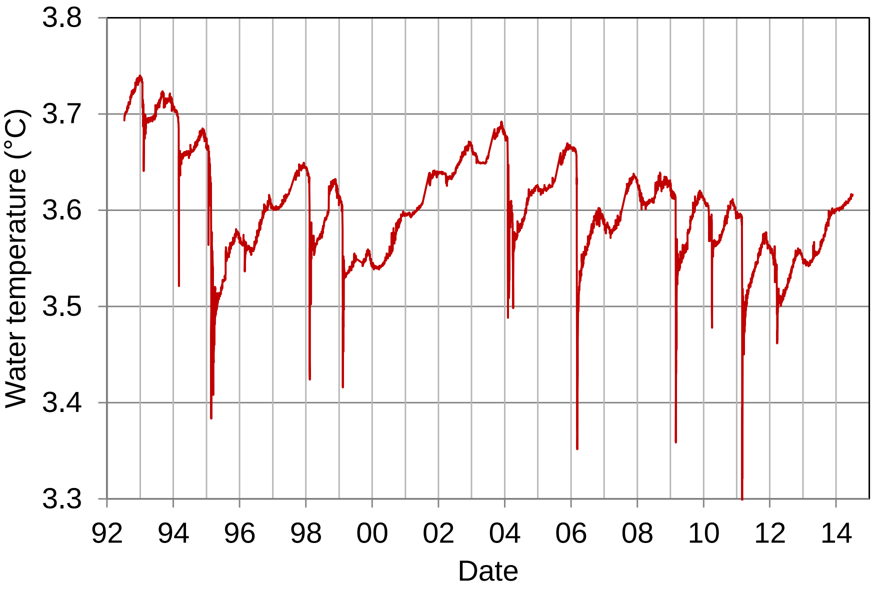
Since 1992

The depth, timing, and frequency of vertical water column mixing are among the most important processes in lakes. In deep lakes, vertical mixing often controls the subsequent algal biomass in upper layers since it redistributes nutrients stored deep in the water column. Vertical mixing to great depth is also the primary process that replenishes dissolved oxygen near the lake bottom that is otherwise depleted by the decomposition of organic material raining down from above.

The Crater Lake monitoring program uses detailed water temperature data to evaluate deep-water mixing events in winter. The water temperature near the bottom (550 m) is continuously measured using precision data-logging temperature sensors. Temperature at this depth is variable through time, showing periods of increase due to geothermal heating punctuated by significant drops in temperature. These downward spikes indicate discrete mixing events when cold water floating on top of the lake was forced down to the lake bottom through a process called thermobaric instability. Significant mixing events have occurred in 12 of the last 26 years.

It is important to note that thermobaric instability requires reverse stratification of the lake in winter, which exists when extremely cold water floats on top of the lake. The concern is that warmer fall and winter air temperatures associated with warming climate might occur more often and prevent the formation of reverse stratification in the future and therefore prevent deep-water mixing for extended periods. Impacts from less frequent mixing might include an initial increase in clarity in non-mixing years due to less upward mixing of deep-water nutrients, followed by reduced clarity when the lake did eventually mix. Bottom waters could eventually become anoxic causing “deadzone” conditions for bottom dwelling animals. A project is currently underway with the USGS Oregon Water Sciences Center to model the influence of climate on deep-water mixing in Crater Lake and accurately predict the impact of warming climate conditions.

*Much of our understanding of deep-water mixing events and vertical nutrient flux in Crater Lake results from research conducted by personnel from the Department of Oceanography at Oregon State University. In particular, we are grateful to Robert Collier, Jack Diamond, Chris Moser, Jim McManus, and Greg Crawford.*

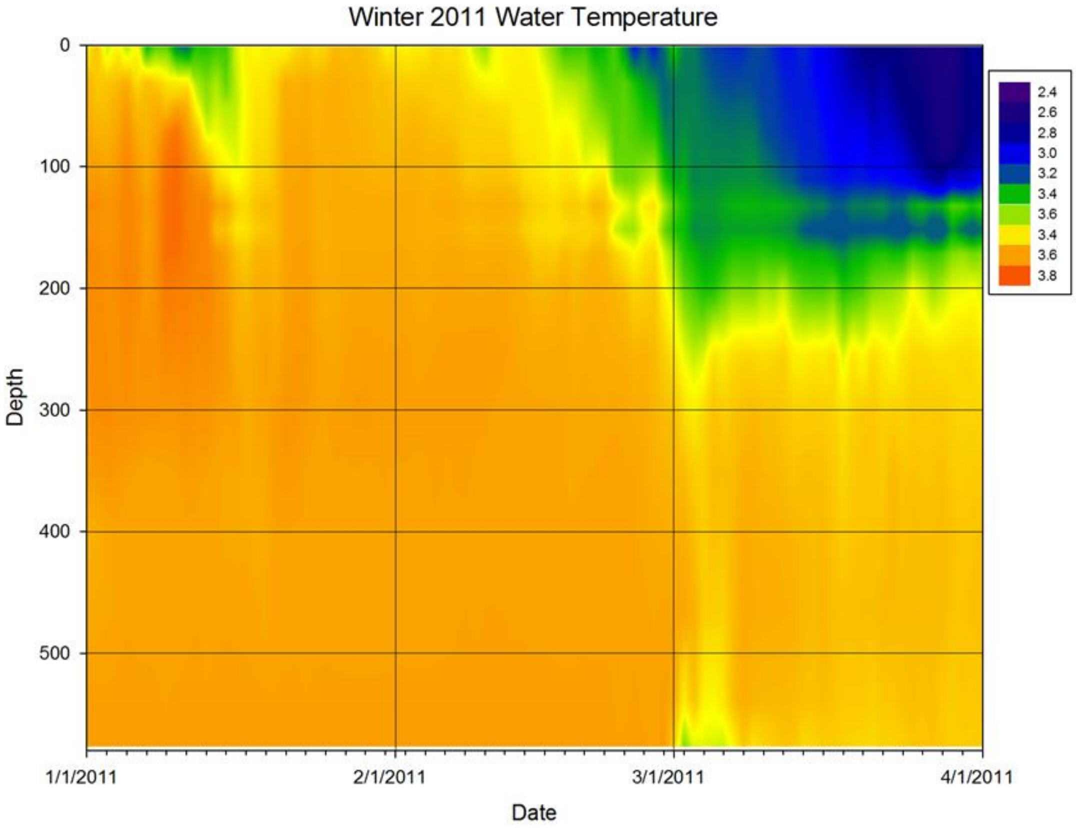


## 7.2 Example Deep-Water Mixing Event

Because of the great depth of Crater Lake, wind and convection only mixes the water column to 200-300 m.  Mixing to the bottom occurs via thermobaric instability which requires reverse stratification within the water column in winter.  The example below shows temperature throughout the water column in winter 2011, including a deep-water mixing event. Relatively small differences in temperature set up these profound mixing events of large masses of water.

In the figure below reverse stratification is readily apparent in the temperature data in February and March, reaching a depth greater than 200 m (blue and green colors at the top).  The deep-water mixing event occurred at the beginning of March, characterized by the sudden appearance of colder water at the lake bottom (green color at the bottom around March 1).  It is the sinking of colder and higher oxygenated water from above that replenishes oxygen at the bottom and displaces some of the deep, relatively nutrient rich water upwards.

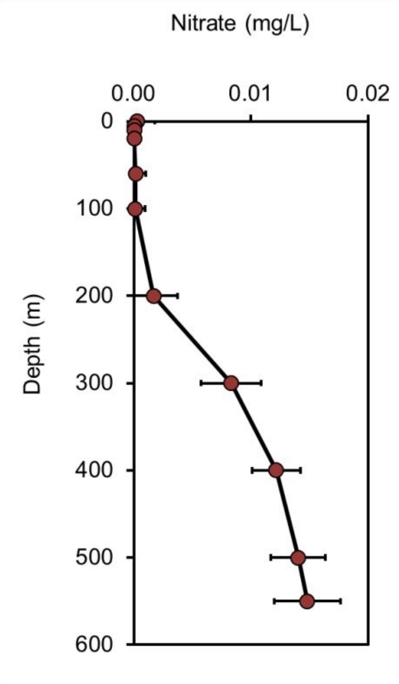
Recovering a SeaBird Electronics temperature sensor after a year in the Crater Lake water column (NPS photo)



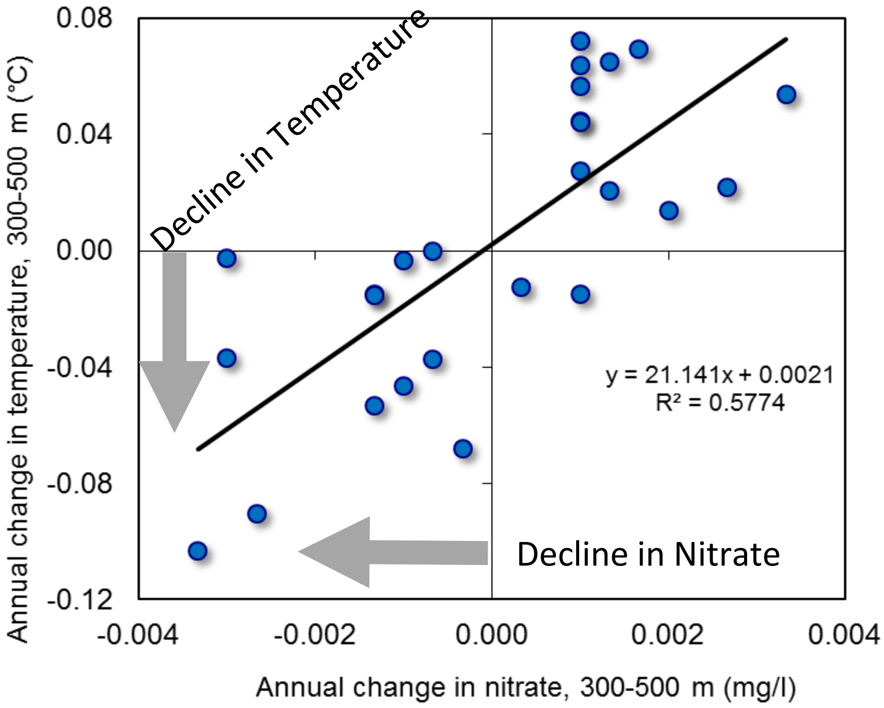
## 7.3 Influence of Winter Mixing on Deep-Water Nitrate Storage

Since 1989

Nitrate is the primary nutrient limiting algal growth in Crater Lake. Nitrate is near zero in the upper lake because it is rapidly taken up by phytoplankton (figure at right). Nitrate increases with depth as organic material "rains" down into the deep lake and decomposes. Mixing to the lake bottom in some winters circulates nutrients upward from deep-water storage where it is then available for the growth of algae the following summer.



The figure below shows the annual change in the concentration of nitrate below 300 m over the last 26 years versus the annual change in deep-water temperature. The lower left corner of the figure indicates years where both nitrate and water temperature below 300 m declined due to the sinking of nitrate poor cold water from above (i.e. mixing events). 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 on the lake bottom (upper right corner of figure).

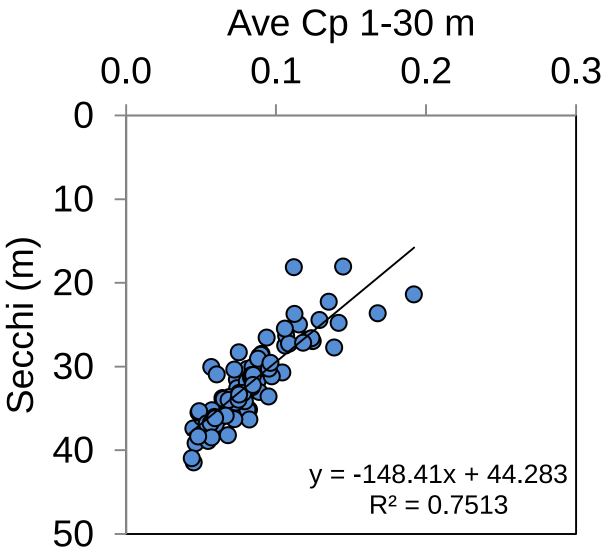


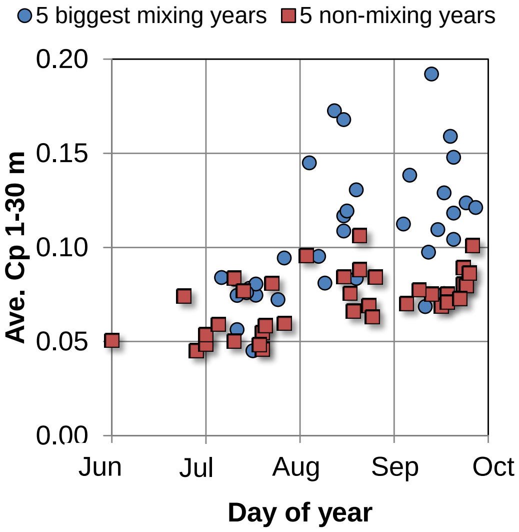
# 7.4 Impact of Winter Mixing on Surface Water Clarity

Since 1988

The transmissometer on the profiling CTD is one of our best tools for studying water clarity (see section 8.2). It provides vertical estimates of algal particle density throughout the water column and has been used regularly since 1988. Although much of the algae in the lake are below 30 m, it is the density of algae in near-surface waters that affects Secchi clarity. Average particle density in the top 30 m of the lake is highly correlated with Secchi depth measured on the same day (left figure) and can therefore be used as a surrogate for water clarity.

The particle density data collected over the last 27 years indicates that deep-water mixing in winter can influence water clarity the following summer. Episodic mixing to the lake bottom during some winters is known to circulate nutrients upward from deep-water storage into the photic zone where it available for the growth of algae and may influence water clarity. The figure below shows summertime particle density in the top 30 m for the 5 biggest (**blue**) and 5 smallest (**red**) mixing years. All years start off the summer with few algal particles. However by August, years following deep-water mixing events tend to have more algae and lower clarity than non-mixing years. Therefore, some of the long-term variability in water clarity through time appears to be influenced by the presence or absence of deep-water mixing events, and the upwelling of nutrients during the previous winter.

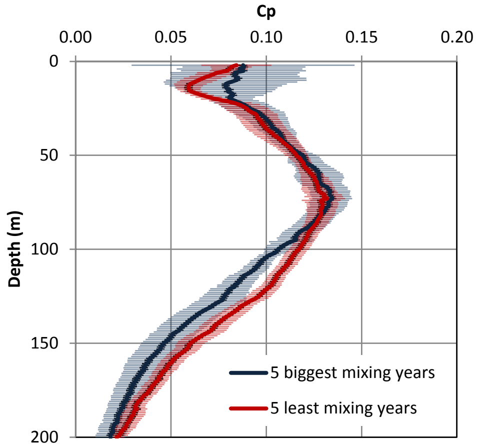




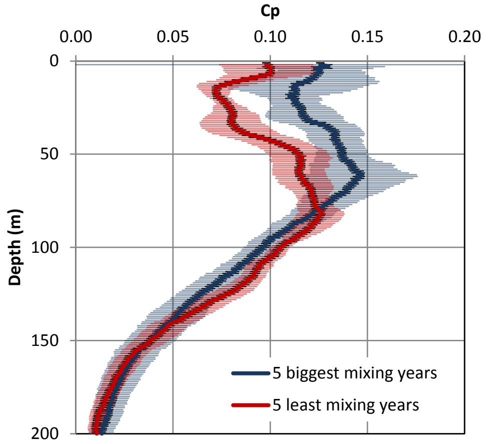
## 7.5 Impact of Winter Mixing on Phytoplankton Particle Density

Mixing to the lake bottom in some winters is known to circulate nutrients upward from deep-water into the photic zone where it can potentially affect the growth of algae the following summer. Particle density data collected since 1988 suggest that episodic mixing events can indeed have an impact on algal growth throughout the photic zone. Significant deep-water mixing events have occurred in 12 of the last 26 years. The figures at right compare the mean monthly particle density in the 5 biggest mixing years (**blue**) and 5 non-mixing years (**red**) (horizontal lines are 95% confidence intervals). In July, there is not much difference in particles between mixing and non-mixing years at any depth. However, in August and September the number of particles from the surface down to approximately 80 m tends to be higher in mixing years.

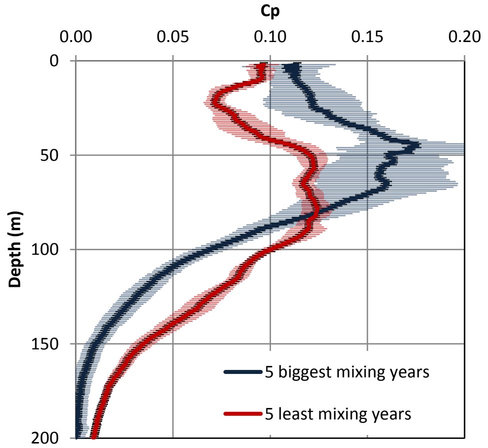
July Cp & mixing (n=31)



Aug Cp & mixing (n=20)



Sept Cp & mixing (n=30)

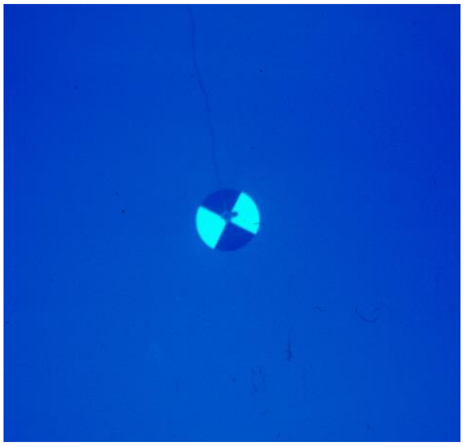


# 8. OPTICAL PROPERTIES

## 8.1 Secchi Disk Water Clarity

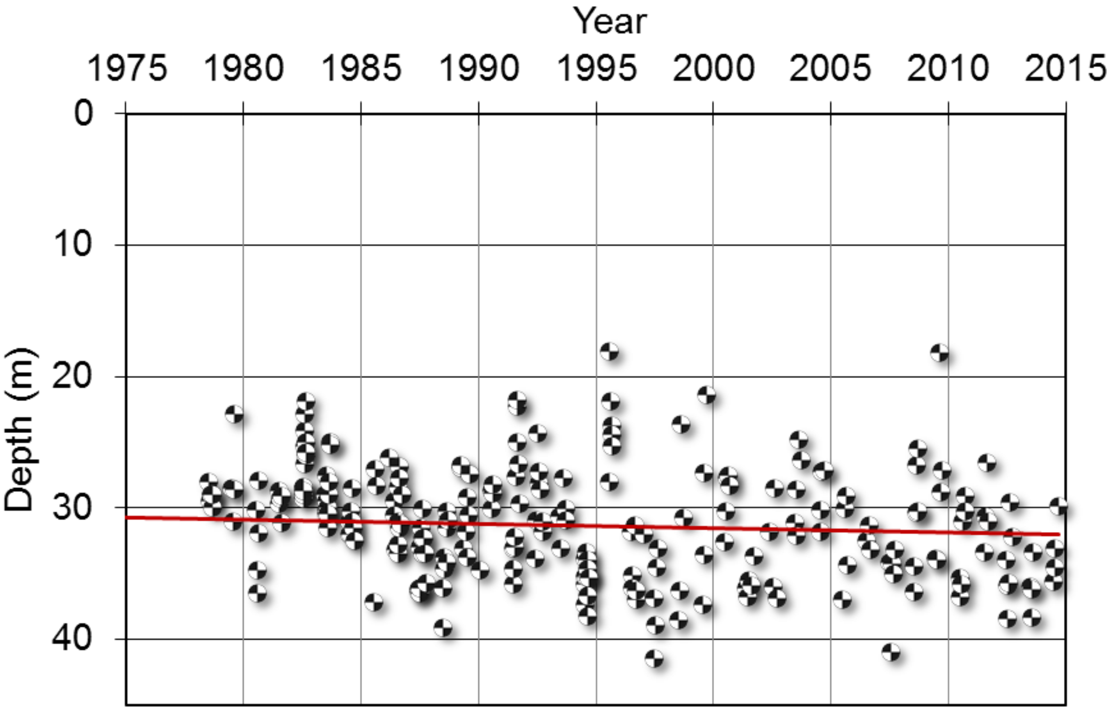
Since 1978

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 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. To standardize the process the measurements are only taken between the hours of 10:00 am and 2:00 pm, and only during calm lake surface conditions. 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.



Secchi disk in Crater Lake (NPS photo)

The first clarity measurement in Crater Lake was conducted by USGS researcher Joseph Diller in 1896 by using a white dinner plate lowered into the lake. Consistent annual 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 (p=0.028).



## 8.2 Particle Density and Water Clarity

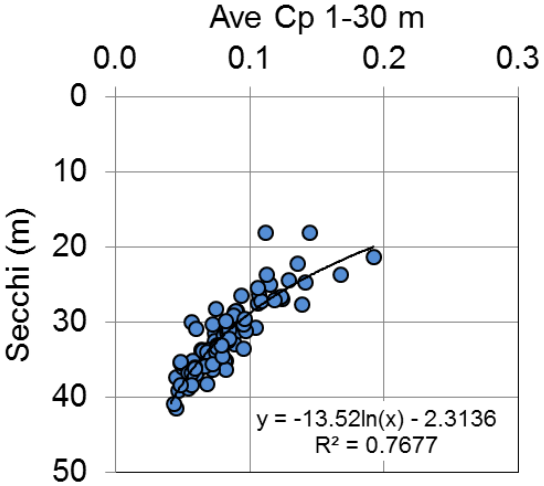
Since 1988

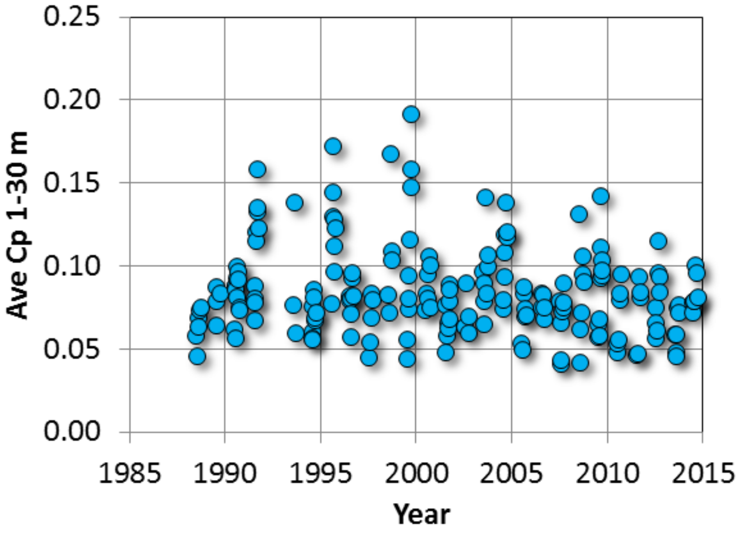
**OPTICAL PROPERTIES**

The beam transmissometer is one of our best tools for measuring water clarity, and has been used at Crater Lake since 1988. It 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 calm, resulting in fewer occasions when the Secchi disk can be used.

CTD package used at Crater Lake. Tall black sensor on left is transmissometer. (NPS photo)

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, calculated from the transmissometer in the top 30 m of the lake is highly correlated with Secchi disk depth measured on the same day (figure on left below) and can be used as a surrogate for Secchi disk water clarity. Neither Secchi disk (section 8.1) or particle density indicate a decline in water clarity near the surface through time.



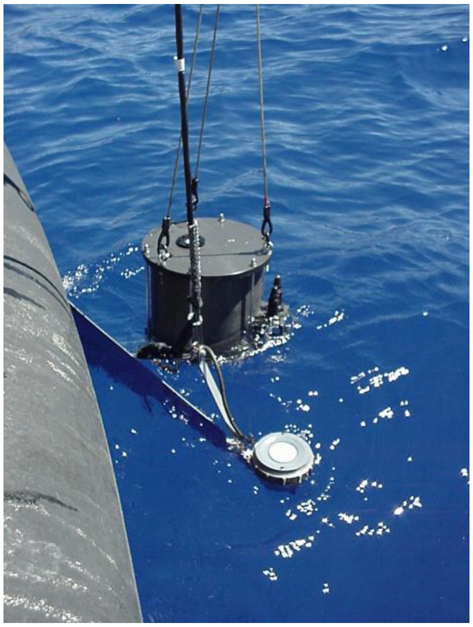


## 8.3 Depth of Light Penetration

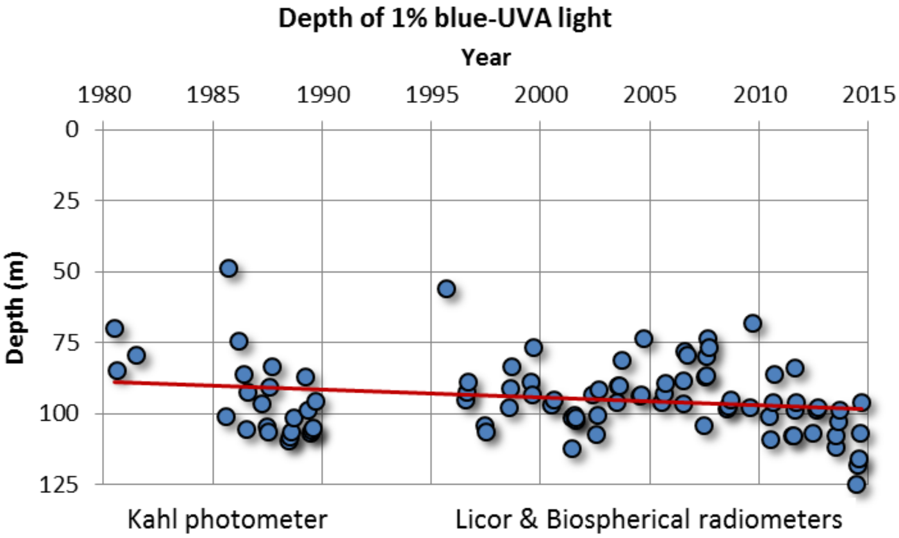
Since 1980

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 (with fewer particles like phytoplankton, pollen, or dust) and shallower in lakes with more particles. 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 3 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 to why the lake appears blue). The depth where 1% of the surface blue-light intensity remains in Crater Lake is typically around 100 m in depth (figure below). 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)

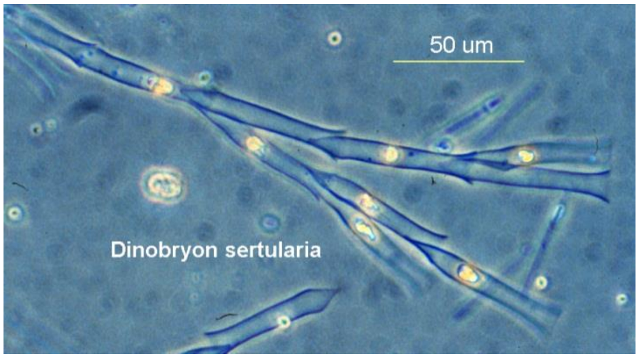


# 9. BIOLOGICAL PARAMETERS

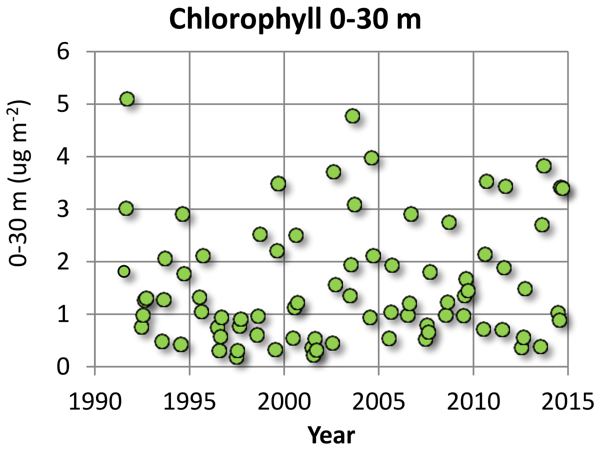
## 9.1 Chlorophyll: Phytoplankton Abundance

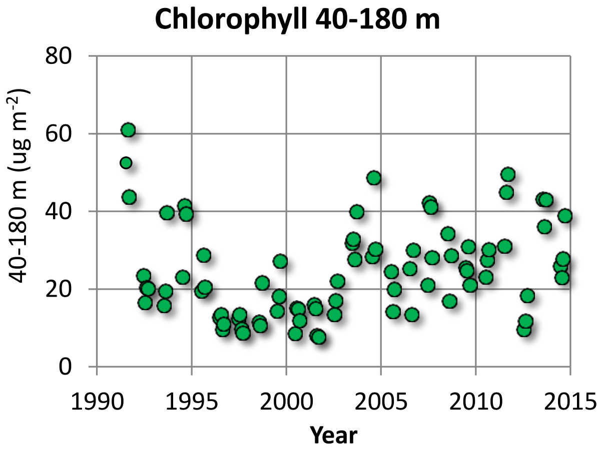
Since 1991

Chlorophyll concentration is often used as a surrogate for phytoplankton abundance, the base of the food chain in aquatic systems. Chlorophyll in Crater Lake is measured once per month during the summer at 17 depths in the water column between the surface and 300 m. Chlorophyll concentrations are extremely low compared to most lake systems. Chlorophyll values in the top 30 m vary widely over the summer with lowest readings typically soon after the onset of stratification. The data also show high year-to-year variability with no clear long-term trend through time.



The algae Dinobryon sertularia from Crater Lake (NPS photo)



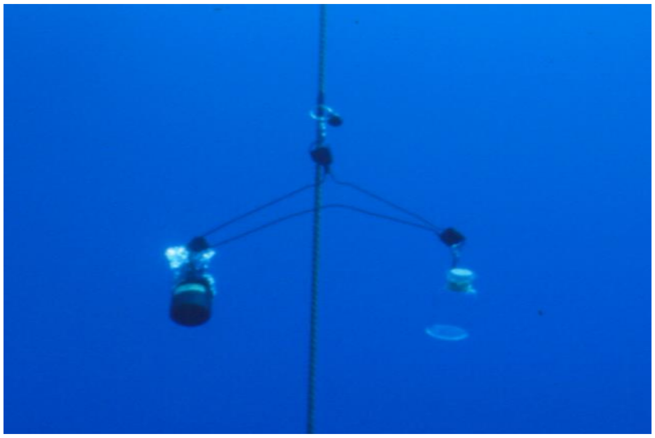


## 9.2 Primary Productivity: Phytoplankton Growth

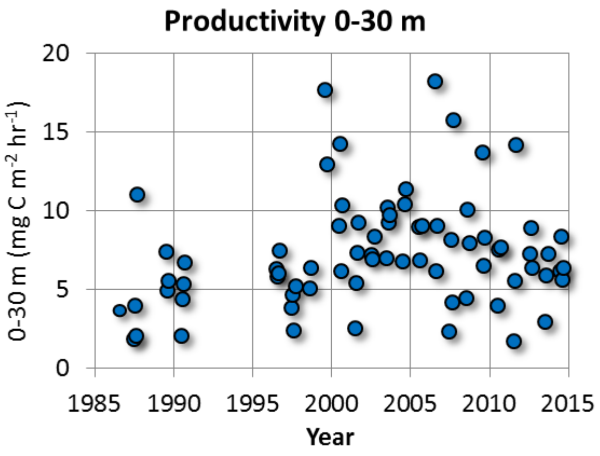
Since 1987

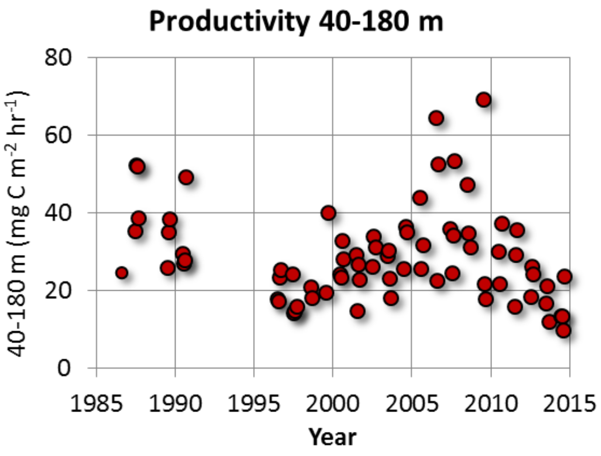
## BIOLOGICAL PARAMETERS

Primary productivity measures mid-day growth rate of phytoplankton within the lake and is measured once monthly during the summer at 13 depths within the water column between the surface and 180 m. Primary productivity is expressed in units of carbon added by phytoplankton (micrograms) per hour for a given water volume (cubic meters). It is 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 at that time. There is a high degree of year-to-year variability in primary productivity and no clear trends through time.



Primary productivity light and dark bottles incubating in Crater Lake (NPS photo)



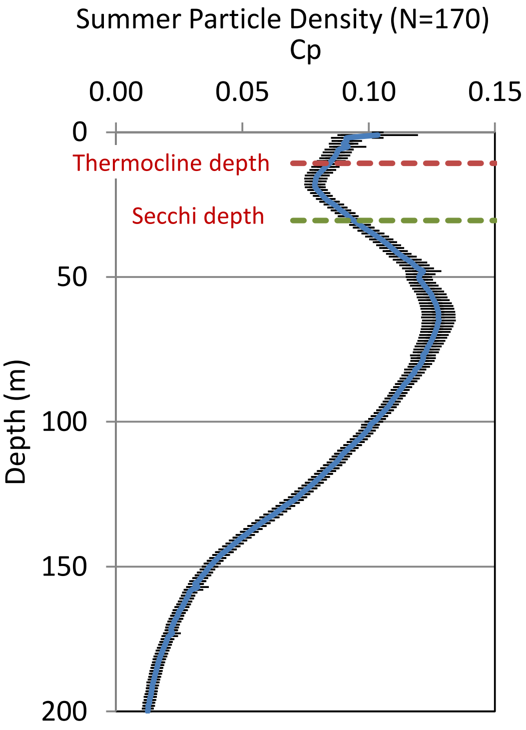


## 9.3 Phytoplankton Particle Density

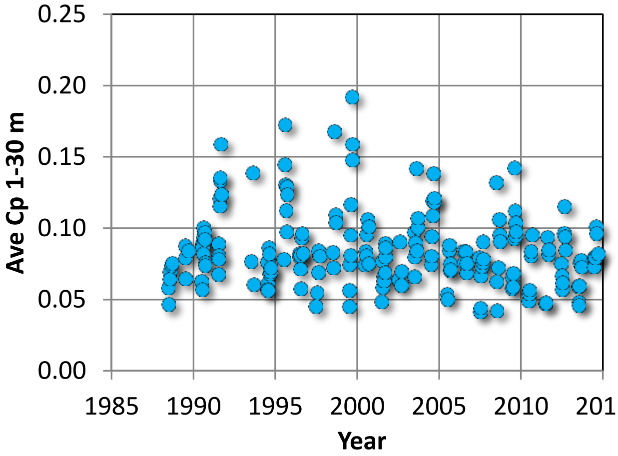
Since 1988

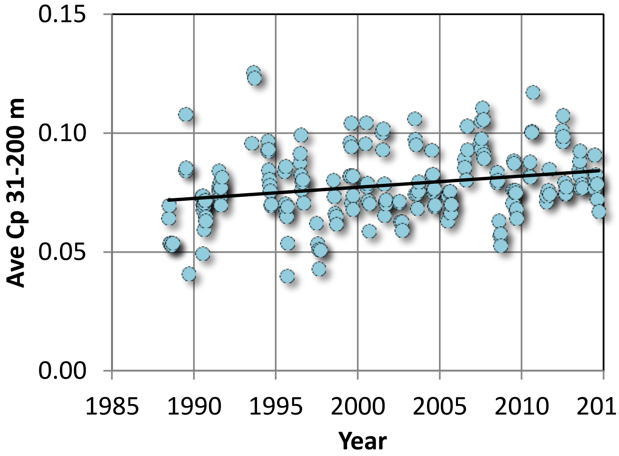
Particle density is a good proxy for estimating phytoplankton abundance in Crater Lake. The density of particles in the water column has been measured since 1988 with a beam transmissometer on the profiling CTD. Multiple profiles per month are typically collected during the summer. Because particles in CRLA are primarily phytoplankton, the vertical pattern in particle density (at right) shows the characteristic distribution of algae within the Crater Lake water column during summer stratification. Two phytoplankton communities typically develop in the summer, one in the warm water floating near the surface and a deeper group typically peaking around 60 m. (See phytoplankton composition section 9.4)

The long-term trend data indicates that the particle density of the shallow community has not changed significantly since 1988 (below). However, the deeper group may have increased slightly over the monitoring period (p=0.004).



A transmissometer is an instrument that measures the fraction of a light beam that passes through a set distance of water. It is affected by both water absorption and scattering by particles.



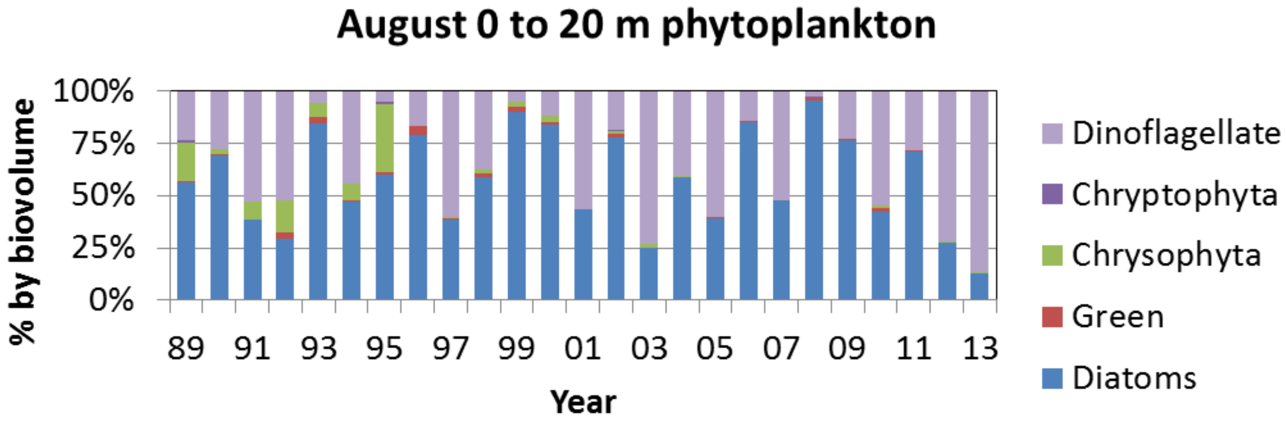


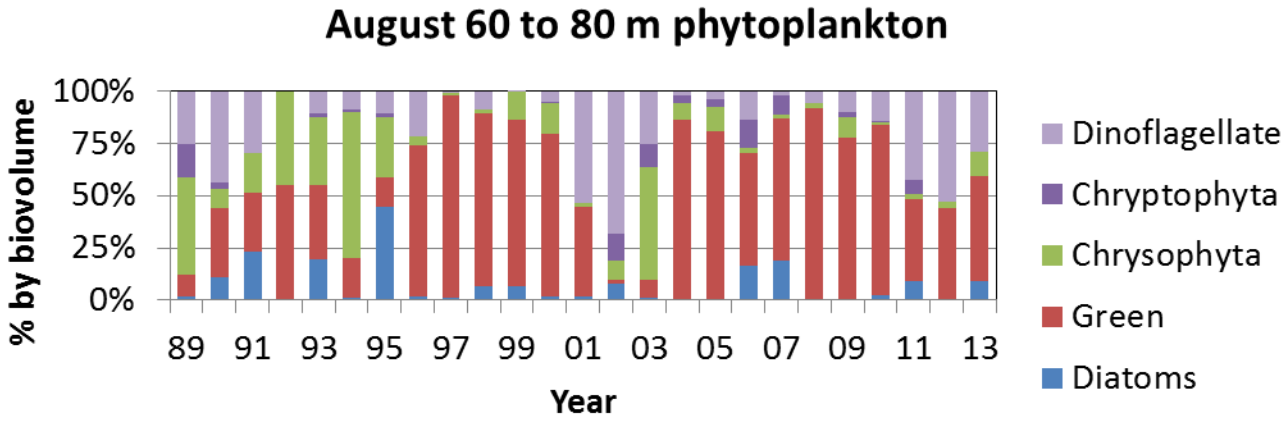
## 9.4 Phytoplankton Composition

Since 1989

Free-floating phytoplankton are the base of the food-chain in deep lakes. The phytoplankton within the summer water column of Crater Lake form two distinct communities separated by the thermocline. Algae in the warm water near the surface are almost completely dominated by a few relatively large size diatoms and dinoflagellates, whereas deeper depths are much more diverse. Since 1989, the near-surface algae have 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.

The chrysophyte algae Dinobryon sertularia from Crater Lake (NPS photo)



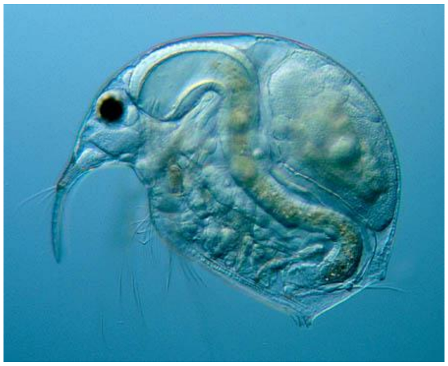


## BIOLOGICAL PARAMETERS

## 9.5 Zooplankton Composition

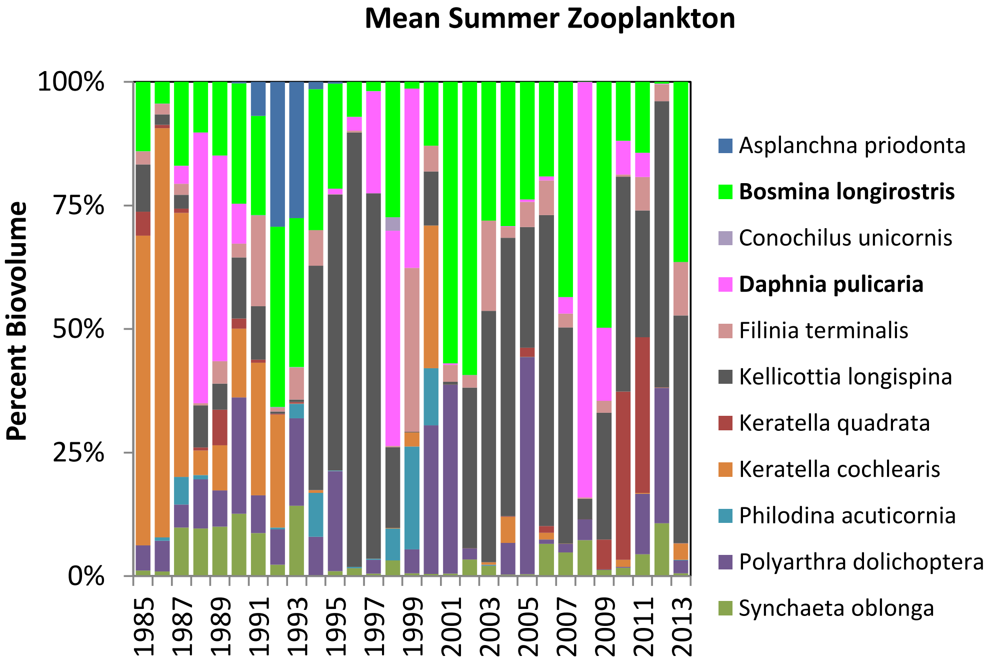
Since 1985

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* & *Bosmina*) and nine rotifers dominate the offshore community. The water flea *Daphnia* is the lake's largest zooplankter (2 mm long) and it's abundance through time is strongly controlled by predation from introduced kokanee salmon(see section 9.6). *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 CRLA 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/DiscoverLife.org)**



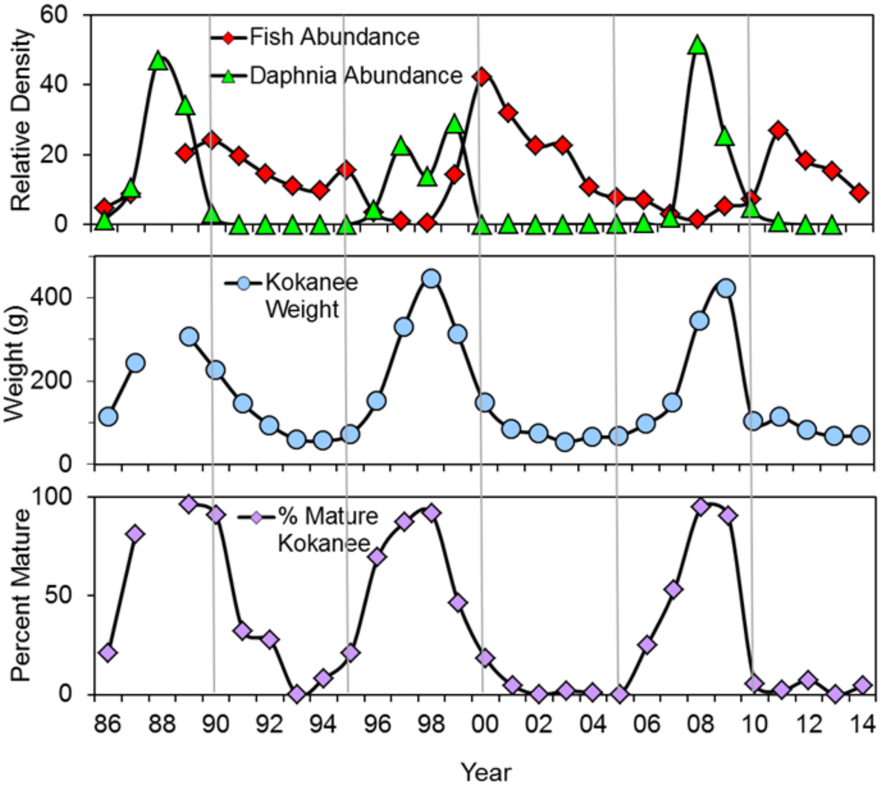
## 9.6 Impact of Fish on Daphnia

Since 1985

## BIOLOGICAL PARAMETERS

The water flea *Daphnia* is the lake's largest zooplankter (≈2 mm long) and it's abundance through time within Crater Lake is strongly controlled by predation from kokanee salmon. Kokanee (landlocked Sockeye salmon) are primarily plankton feeders that were introduced to the lake in the early 1900's. Kokanee in Crater Lake show a distinct 'boom & 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 is high (**red**), the fish literally 'eat themselves out of house and home' and nearly all of the *Daphnia* (**green**) disappear from the water column for several years. The kokanee population then slowly declines due to food scarcity with few if any fish reaching sexual maturity (**purple**). After 6-7 years of declining fish density, food resources recover (including *Daphnia*) and the few remaining fish attain large size (**blue**) and spawn successfully leading to a rapid rise in density and the cycle resumes.

**Daphnia (Photo: Paul Hebert)**



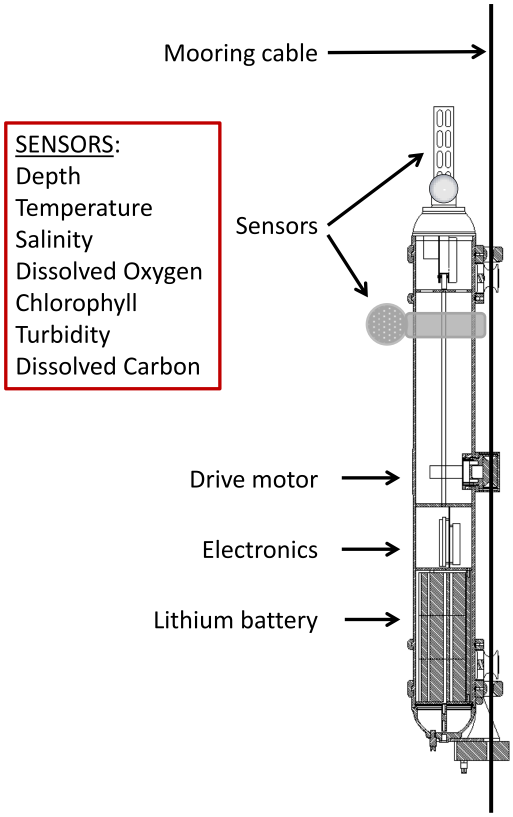
# 10. SPECIAL PROJECTS

## 10.1 Autonomous Profiling Instrument

The first year-round study of detailed daily biological conditions throughout the Crater Lake water column has been collected using a state-of-the-art ITP profiling instrument (McLane Labs, Falmouth, MA). The monitoring program has long recognized that studying the lake during non-summer periods is crucial for understanding the health and function of the lake system because important physical, chemical, and biological processes occur during these times. Unfortunately, weather conditions make it extremely difficult for researchers to access the lake in the fall, winter, and spring. The ITP instrument resides in the lake year-round and provides our first detailed insight into lake conditions outside the summer season.

Woods Hole Oceanographic Institute initially designed the ITP instrument for studying deep-water ocean conditions under the floating Arctic ice-pack (www.whoi.edu/page.do?pid=20756). In the Arctic, 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 battery powered instrument crawls up and down a wire mooring anchored to the bottom of the lake and is kept upright with floats near the surface. During the ITP's once daily round-trip, data is collected every 1-2 m for chlorophyll concentration, particle density (turbidity), dissolved oxygen, dissolved organic matter, temperature, and salinity. See section 10.2 for the first year results.

> Crater Lake is one of only two lakes in the world using an ITP for studying year-round deep-lake conditions (the other is Flathead Lake, MT). Over 80 ITPs have been deployed in the arctic.

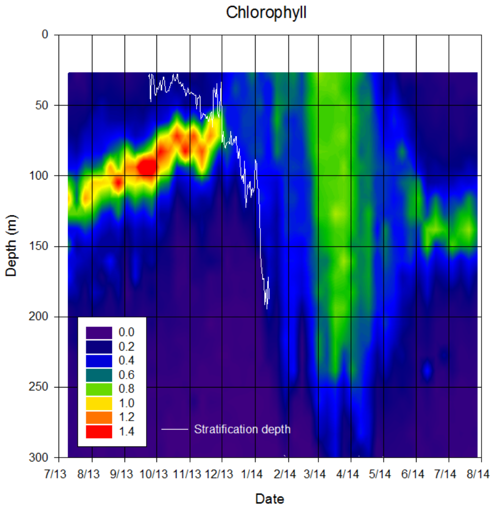


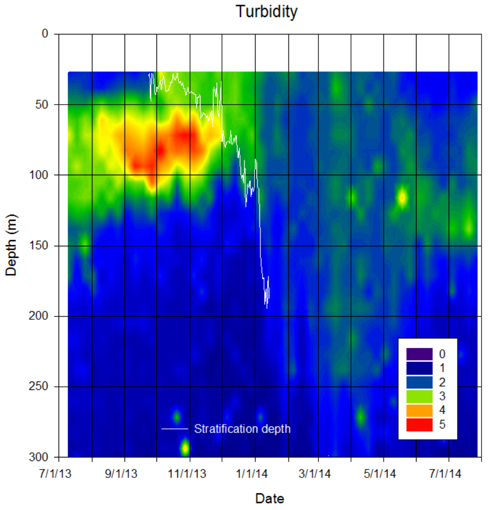
Schematic of ITP profiler in Crater Lake

Biological Technician Kristin Beem helping attach the Crater Lake ITP profiler to its wire mooring line (Photo Kristin Beem)

## 10.2 Autonomous Profiling Results

The ITP moored in the deep basin of the lake collects data on chlorophyll, particle density (turbidity), dissolved oxygen, dissolved organic matter, temperature, and salinity The profiler sleeps at 560 meters and wakes up once daily to travel to 30 m depth and back collecting data along the way. The profiler provides unprecedented detail both vertically within the water column (every 1-2 m) and over short time scales (daily) that are simply not feasible with traditional boat-based sampling. Just as important, it provides our first detailed view of biological conditions during the fall, winter, and spring periods when extreme weather otherwise prevent lake access. Much has been learned about the lake in this first full-year deployment. The figures below show chlorophyll and particle density data as colored depth-time contour plots over an entire year (July 2013-August 2014).


Chlorophyll


Turbidity

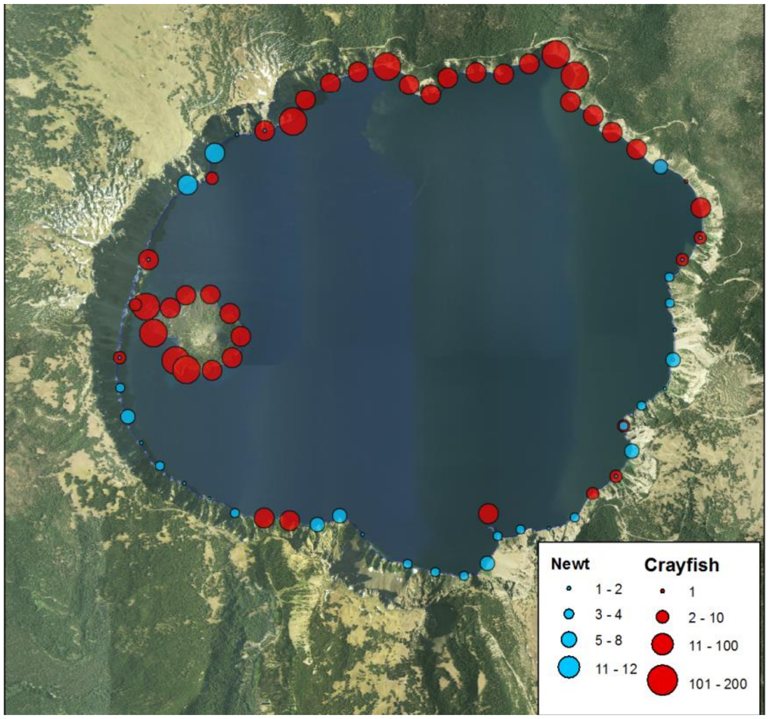
Highlights of the 2013-2014 profiler deployment:

- Spring Algal Bloom: An algal bloom occurred during spring mixing prior to the onset of stratification and prior to summer lake access (≈ from Feb-15 to Apr-15). The bloom lasted almost 2 months and reached extremely deep depths (≈250 m) due to mixing of the upper water column. It ended abruptly with the onset of stratification in mid April. Prior to the ITP, the lake had only been sampled during spring mixing during one day in 1989. Variability in the duration and depth of the spring bloom may affect the availability of nutrients and clarity during the summer.
- Deep Chlorophyll Maximum (DCM): The presence of a DCM is a characteristic particular to unproductive lake and ocean systems. The vertical location of the DCM is considered a sensitive indicator of the overlying water column conditions. The profiler data shows a remarkable shallowing of the DCM depth over the summer & fall (120 m to 75 m), which is critical to recognize when interpreting historic long-term DCM depth data that is only collected on a monthly basis.
- Deep-water Oxygen Depletion: (Not shown here) The oxygen sensor captures annual and seasonal rates of oxygen depletion in the deep lake from the decomposition of organic material, and fluxes of oxygen in the upper lake associated with photosynthesis. This may help estimate whether anoxia is likely to occur in the future if warming air temperature reduces the frequency of deep-water mixing events.
- Seiche Activity: The chlorophyll, turbidity, and oxygen data all show evidence of seiche activity (internal deep-water waves) in the lake during summer stratification. The presence of such waves are caused by surface winds and can affect vertical and horizontal movement of nutrients and plankton.

## 10.3 Native Newts & Invasive Crayfish

Non-native crayfish (*Pacifastacus leniusculus*), introduced to Crater Lake in 1915, are replacing a unique population of native salamanders. Rough-skinned newts in Crater Lake, known as the Mazama Newt (*Taricha granulosa mazamae*), are morphologically, genetically, and physiologically distinct from populations of rough skinned newts (*T. granulosa*) outside the Crater Lake caldera. A special project was initiated in 2008 in conjunction with the University Nevada Reno and USGS to assess the impact of crayfish on benthic organisms in Crater Lake. Snorkel survey and trapping results since 2008 indicate that crayfish have expanded since their introduction to occupy nearly 80% of the lake shore. Historical observations by park naturalists and biologists suggest a decline in newt distribution through the 1900’s. Newts remain in areas that crayfish have yet to invade but are virtually absent from areas occupied by crayfish.

Isotopic signatures of carbon and nitrogen from newts and crayfish were evaluated to assess food web trophic position and diet. Shoreline insect diversity and density were evaluated in crayfish and non-crayfish areas to assess the direct impact of insect predation by crayfish and the indirect impact to newts which also use insects as food. Mesocosm (tank) experiments were conducted to investigate crayfish predation on newts and newt behavioral response. Based on multiple lines of evidence, we believe that crayfish are expanding in distribution, and that further expansion will lead to further declines in newt abundance and distribution, and perhaps elimination of the Mazama Newt. The mechanisms of replacement documented by the project include direct predation by crayfish and introduced fish, crayfish avoidance by newts, competition for food and cover, and indirectly increasing newt energy demands and exposure to ultraviolet radiation.



Crayfish and Newt relative abundance from snorkel surveys in 2012