VERTICAL TEMPERATURE STRUCTURE IN CRATER LAKE, OREGON

ABSTRACT

Vertical temperature profiles taken at different seasons in Crater Lake show an isothermal layer at middepth (295 m) with hyperadiabatic temperatures below that point. The lake is apparently meromictic, with circulation limited to the waters above middepth.

One of the most important physical aspects of Crater Lake, the vertical temperature profile, has not received sufficient study. Kibby et al. (1968) mention uncertainties in the literature regarding thermal stratification in the lake and suggest that uncertainty has arisen because some measurements may have been taken in upwelling sections of the lake where thermal stratification would not be evident. Kemmerer and others (*cited in* Wright 1931) reported a temperature of 3.5C at 600 m (before the depth of the lake was accurately known), with all temperatures deeper than 100 m being <4.0C. A comprehensive review of temperatures measured in Crater Lake was given by Nelson (1961). According to Nelson, Everman reported temperatures of 61F (16C) at the surface, 41F (5C) at 169 m, and 46F (7.8C) at 495 m, although studies since Everman's show a gradual decrease in temperature to the bottom with the lowest bottom temperature of 3.1C being reported by Rowley in 1954. A more recent report on the vertical temperature in Crater Lake, mentioned by Volchok et al. (1970), is that of Covey and Egeberg (in August 1967) who found temperatures of 17C at the surface, 10C at about 13 m, with temperatures decreasing slowly to 4.5C at 70 m, then gradually becoming quite uniform at 4.1C. The only profile deeper than 244 m indicated an increase in temperature of almost 0.5° from 300 m to the bottom.

Our interest in the temperatures of Crater Lake began in June 1969 when we first looked for evidence of temperature microstructure (Neal et al. 1971). All deep temperature measurements taken at that time revealed an isothermal zone (3.53C) centered at middepth (about 295 m). All profiles indicated that below that zone temperature increases with depth. We therefore decided to make additional measurements during the cold months to see whether the deep temperature structure changes and whether the lake completely overturns.

We are grateful to all Crater Lake National Park Service employees who helped us with the fieldwork and to Crater Lake Lodge, Inc., for use of their boat. We appreciate the extra time devoted to preparation and calibration of instruments by D. Keene. Suggestions offered by D. Caldwell have been extremely helpful.

PROCEDURE

In late June 1969 we obtained temperature profiles, usng XBTs both as regular free-fall probes and with drag chutes (Denner et al. 1971). During July 1969 a temperature-depth profiling system was used to obtain profiles from the surface to the bottom. In September 1970 we lowered an XBT probe to the bottom by handwinch. Temperatures were obtained at discrete depth intervals. This procedure was used for all subsequent measurements.

Summer conditions prevailed when measurements were made in late June 1969, July 1969, and September 1970. Winter conditions prevailed in February and early May 1970 and spring conditions at the time of our measurements in June 1971. Additional efforts to obtain profiles under fall, winter, and spring conditions were unsuccessful.

LIMNOLOGY AND OCEANOGRAPHY



FIG. 1. Representative temperature profiles taken during winter, spring, and summer conditions.

RESULTS

Representative profiles for spring, summer, and winter conditions are shown in Fig. 1. All profiles, regardless of location and the time at which they were taken, have several interesting features in common. At middepth (295 m) all profiles pass through 3.53C. During warm season conditions (when the lake's surface is above 4.00C) this point represents the temperature minimum. An isothermal layer ranging from at least 10 to 40 m thick is found at middepth. Below this layer the temperature increases to the bottom. Near the bottom another isothermal zone is usually found; however, its temperature was higher (3.69C) in September 1970 than at any other time of measurement. The average temperature difference between middepth and the bottom water was 0.11°. When the probes struck bottom an abrupt increase in temperature was observed; the bottom sediment temperature averaged 3.80C or about 0.12° warmer than water 10 m above the bottom.

In February a thin layer of ice covered much of the shoreline area in the northeast part of the lake. Although no ice was seen on the lake in May, the surface temperature averaged about the same as it did in February, 2.5C.

The profiles taken in February, May, and June (1971) all showed isothermal layers scattered throughout the water column. No attempt was made to locate the exact boundaries of these layers, but they had to be at least 10 m thick to be detected by our 10-m sampling interval. The profile taken in June 1969 showed distinct layering below middepth. The September 1970 profile showed the least amount of layering, possibly because readings generally were taken at greater intervals of depth.

DISCUSSION

Values of the change in the temperature of maximum density of freshwater with increasing pressure have been derived by Eklund (1963) and more recently by Kell (1970). This change, $\delta T_{\rho}/\delta z$, based on Kell's report is:

$$\delta T_
ho/\delta z = 1.96 imes 10^{-3}~{
m C/m}.$$

We have drawn the line generated from this expression in Fig. 1. The line intersects the surface at 4.00C (Eisenberg and Kauzmann 1969) and the maximum depth of the lake (z_{max}) at 2.85C. Vertical temperature profiles that cross this line should change sign of slope upon crossing since a stable water column must have density increasing with depth (Eklund 1965).

Eklund (1965) has shown that the temperature of maximum stability T_s in lakes near the temperature of maximum density T_{ρ} varies with depth z as follows:

$$\delta T_s/\delta z = \delta T_\rho/2\delta z.$$

We have also included the line corresponding to this expression in Fig. 1.

Temperatures in Great Bear Lake (N.W.T.) (in the early part of the season) crossed the line of maximum density at the point of maximum temperature (Johnson 1966). In April 1965, Great Bear Lake was isothermal at the temperature of maximum stability at the bottom (3.53C) from middepth to the bottom.

The temperature profiles we have measured in Crater Lake differ markedly from those obtained by Johnson in Great Bear Lake. The Crater Lake profiles do not reach a maximum where they cross the line of maximum density, neither do they show a change in sign of slope at that point. Crater Lake has an isothermal layer (3.53 C) at middepth ranging from at least 10 m to at least 40 m thick. Below that layer the temperature is hyperadiabatic. The temperature at middepth (3.53C) does not approach the temperature of maximum stability at the bottom (3.42C). Yet the water below middepth must be stable since the deep profiles obtained over a period of 2 years show the same relative temperature gradients.

For the deep waters to be stable there must be some substance in them to compensate for the decrease in density caused by the increase in temperature. Various reports indicate that such substances may be found in the deeper waters. The U.S. Coast and Geodetic Survey made a survey of Crater Lake in 1959 and reported the specific gravity of the water ranged from 0.9991 near the surface to 0.9996 at the bottom (Nelson 1961). Bottom water with fine pumice in suspension has also been reported as having a salinity reading of 1.3 and a specific gravity of 1.000 (Williams [cited in Nelson 1961]). In a further discussion of the "salinity" of the lake, Nelson mentioned a range of 0.0 at the surface to 0.5 at the bottom. Although there are reports suggesting substances in the deeper waters, full identification of the materials has not been reported.

Temperature structure in freshwater lakes generally determines the vertical circulation. Since no deep circulation studies have been made and the temperature structure has not been well known, various workers have had to speculate on the vertical circulation in Crater Lake. Volchok et al. (1970) noted that concentrations of strontium-90 and cesium-137 were nearly constant at all depths, but tritium decreased with depth. They assumed, however, that complete and thorough mixing occurs in Crater Lake. Simpson (1970) also assumed that the lake mixes vertically, with a time constant on the order of 1 year. However, Strøm (1945), on the basis of data available to him believed that Crater Lake was more or less meromictic. Nelson (1961), after considering reports of tritium concentrations in the lake, felt that no definite conclusions could be made regarding vertical circulation.

As a result of our measurements we believe that Crater Lake is meromictic. The extent of vertical mixing appears to be limited to the upper 295 m. The question of how radioactive fallout reaches the bottom waters remains unanswered. It is possible that radionuclides adhere to pollen and dust particles that settle to the bottom of the lake (Nelson 1967).

VICTOR T. NEAL

Stephen J. Neshyba

WARREN W. DENNER¹

Department of Oceanography, Oregon State University, Corvallis 97331.

REFERENCES

- DENNER, W. W., V. T. NEAL, AND S. J. NESHYBA. 1971. A modification of the expendable bathythermograph for thermal microstructure studies. Deep-Sea Res. 18: 375–378.
- EISENBERG, D., AND W. KAUZMANN. 1969. The structure and properties of water. Oxford. 296 p.
- EKLUND, H. 1963. Fresh water: temperature of maximum density calculated from compressibility. Science 142: 1457–1458.
- perature of maximum density. Science 149: 632–633.
- JOHNSON, L. 1966. Temperature of maximum density of fresh water and its effect on circulation in Great Bear Lake. J. Fish. Res. Bd. Can. 23: 963–973.
- KELL, G. S. 1970. Isothermal compressibility of liquid water at 1 atm. J. Chem. Eng. Data 15: 119–122.
- KIBBY, H. V., J. R. DONALDSON, AND C. E. BOND. 1968. Temperature and current observations in Crater Lake, Oregon. Limnol. Oceanogr. 13: 363-366.
- NEAL, V. T., S. J. NESHYBA, AND W. W. DENNER. 1971. Temperature microstructure in Crater Lake, Oregon. Limnol. Oceanogr. 16: 695– 700.
- NELSON, C. H. 1961. Geological limnology of Crater Lake, Oregon. M.S. thesis, Univ. Minn. 175 p.
- ——. 1967. Sediments of Crater Lake, Oregon. Bull. Geol. Soc. Amer. 78: 833–848.

¹U.S. Naval Postgraduate School, Monterey, California.

SIMPSON, H. J. 1970. Tritium in Crater Lake,

Oregon. J. Geophys. Res. 75: 5195-5207. STRØM, K. M. 1945. The temperature of maximum density in fresh water. Geofys. Publ. Norske Vidensk.-Akad. Oslo 16(18): 3-14.

Volchok, H. L., M. FEINER, H. J. SIMPSON, W.

ALGAL POPULATIONS IN ARCTIC SEA ICE: AN INVESTIGATION OF HETEROTROPHY^{1,2}

ABSTRACT

Complex algal populations in the bottom few centimeters of arctic sea ice are accompanied by bacteria, protozoans, and other organisms. Community uptake of dissolved organic substances, assayed with ¹⁴C-glycine, ¹⁴C-glucose, and ³H-acetate, was slow. Microscopic examination of autoradiographs suggests that heterotrophic metabolism by the algae was negligible and that assimilation of the added substrate was almost exclusively by bacteria.

Although the mode of survival of photosynthetic organisms in environments where long periods of darkness prevail remains an unsolved problem, the subject is receiving considerable attention (Rodhe 1955; Bunt and Wood 1963; Wilce 1967; Antia and Cheng 1970). Our report describes an arctic sea-ice community and discusses some results obtained during studies on the metabolism of the algal component of this community. In and below the ice, darkness predominates for nearly half of the year, so that heterotrophy has been suggested. Our study was designed to test for heterotrophic activity of natural populations in ice. The work was carried out in the shallow Chukchi Sea near Barrow, Alaska, in 1970 and 1971. Our intent is twofold. First, a more detailed description of the population composition of the arctic ice algae than hitherto available is included; this is, to our knowledge, the S. BROECKER, V. E. NOSHKIN, V. T. BOWEN, AND E. WILLIS. 1970. Ocean fallout—the Crater Lake experiment. J. Geophys. Res. 75: 1084–1091.

WRIGHT, S. 1931. Bottom temperatures of deep lakes. Science 74: 413.

first time that organisms other than diatoms have been discussed. Secondly, preliminary examination of the heterotrophy problem has produced indications concerning its significance. Although by no means conclusive, our observations agree with those of Rodhe et al. (1966) and Bunt (1963).

We thank C. Person, S. Grant, C. Coulon, and M. Billington for technical assistance and R. J. Barsdate and J. E. Hobbie for reviewing the manuscript. Logistic support was provided by M. C. Brewer and the staff of the Naval Arctic Research Laboratory.

The organisms occur as a brown layer, 2-3 cm thick on the underside of 1-yearold sea ice. Cells are present in the ice all winter, but the visible layer appears in April or May and persists into June. This is the time when the annual ice reaches maximum thickness, about 165 cm. Snow cover varies from none to about 40 cm. The physical character of the ice is more or less uniform from the surface down to the bottom few centimeters; the bottom part where the organisms occur is softer and sometimes rather spongy, especially late in spring. Most of the cells are motile and are probably living in brine pockets (Meguro et al. 1967) which enlarge as the ice melts, thus allowing the cells to move in the ice.

We took samples of the sea ice with corers that cut a core of ice 7.5 cm in diameter. We routinely take three sections about 15 cm in length from the top, middle, and bottom of the core. Cells occur throughout the ice core but are concentrated in the bottom section. The sections are put in covered containers and returned

¹ Financial support was provided under National Science Foundation Grant GB-7800 and by the Arctic Institute of North America through contractual arrangements with the Office of Naval Research.

² Contribution No. 160 from the Institute of Marine Science, University of Alaska.