

Temperature profiles and bathymetry of some high mountain lakes

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The ice cover in high mountain lakes breaks up and disappears in about an hour, in part because it has been divided into fragile vertical spindles, which are individual crystals. Contributing to this process are vertical holes in the ice remaining after particles of dust melt downward as they are warmed by the sun. Temperature profiles of lakes in the Wind River Mountains of Wyoming include those of five lakes in the high wilderness. All are isothermal at or near 5°C below a depth of 20 to 30 m, regardless of elevation or lake depth. Large lakes have a deeper mixed layer than do small ones because of longer fetch and thus more effective wind shear.

It has been a source of wonder to observe the disappearance of ice in the spring melt seasons in high elevation lakes. Those lakes in Sublette County, Wyoming, close enough to roads from which visual observation is possible exhibit a sequence repeated each year. For example, Fremont Lake, 2×10 km in area, develops an ice cover early in January that becomes about half a meter in thickness. Its median day of ice breakup is May 10. Sometime in mid-May, its snow cover gone but the lake appearing completely ice covered, a few narrow cracks appear in the ice sheet shortly before breakup. For no obvious reason, the ice simply disappears in an hour or so, an action that occurs over the whole large lake simultaneously. This action of sheet ice of columnar texture is known, but perhaps needs more description and additional observation.

Hutchinson (1) speaks of “the popular belief that the ice sheet sinks overnight” (ref. 1, p. 530). The explanation of the dissipation of rotting ice seems somewhat incomplete. A desire to look at this and other features of high mountain lakes led me to initiate a program of chemical, bathymetric, and temperature measurements. Some of the results have been published (2, 3).

The ice breakup phenomenon was illuminated by observations gained from canoe navigating in the few cracks or leads in the lake ice a few hours before breakup. The ice of these mountain lakes would fall in the category of sheet ice of columnar texture. It consists of vertical crystals that may extend the entire thickness of the ice sheet. Hutchinson (1) says that the diameter of the columnar crystals ordinarily has a mode of ≈ 2.5 cm, but those crystals observed here are considerably thinner than that, estimated at 5 to 10 mm.

When such ice becomes rotten and unstable through warming, it becomes a mass of closely spaced fragile vertical columns. A moment comes when some of these spindles fail, tipping over and pressing against adjoining columns, and the mass seems to act as a simultaneous domino collapse. So within the hour, lake ice that is miles long, consisting only of needles, quietly disappears.

It has been suggested that the rotting process “involves depression of the freezing point of interstitial water by organic matter precipitated out during freezing” (ref. 1, p. 530). The process observed also may include downward melting of particles of dust or flakes of soot blown by the wind onto the ice, despite the clarity of the air in that part of western Wyoming.

Absorption of sunlight energy by such particles warms them, melting the ice immediately below. Thus, the particles may melt

themselves downward and such migration would separate the ice crystals.

The mechanism of ice breakup is only a small part of the operation of the three-dimensional structure of lake waters. To examine the differences in temperature structure, profiles with depth were measured at different seasons and in lakes of various sizes.

I had previously published bathymetric maps of the largest lakes in Sublette County, Fremont, New Fork, and Willow Lakes (3). In this paper, the maps of the other two major lakes are presented, Boulder and Half Moon Lakes (Fig. 1).

For construction of these maps, the depth readings were obtained by a nonrecording, battery-powered depth sounder that was read at intervals of ≈ 1 min as the boat moved back and forth across the lake. The position of the boat was continually followed by three transits located on the shores. The observers read the azimuth to the boat at intervals of 2 min, with all readings done simultaneously using synchronized watches.

Each instrument man was supported by a note keeper whose clock determined the moment of reading. The azimuth data were plotted, and at each intersection, the depth reading was plotted on the map.

Temperature profiles were measured with an oceanographic reversing thermometer that could be read to 0.01°C . These profiles were measured at one or more locations in the lake in a program separate from the bathymetric mapping.

The lakes for which maps are presented here are about the same size and depth as are the two other medium-size lakes in the vicinity, New Fork and Willow. All four of these lakes are considerably different from Fremont Lake as indicated in Table 1.

Both New Fork and Willow are bisected by terminal moraines representing a halt or a slight readvance in the ice sheet. Such clear division is absent in both Boulder and Half Moon. The terminal moraine of Fremont is complex, consisting of till of both Pinedale and of Bull Lake glaciations. This finding is not observed in the lakes presented here. This double terminal means that Fremont Lake was excavated twice, which may partly account for the fact that it is deeper than the smaller lakes. Fremont also is partly divided by a narrow section where tough bedrock prevented the ice from making the trench uniformly wide. Again, this division is not a feature of any other lakes.

My measurements of the topography of the lake beds were accompanied by only a limited number of temperature profiles. But the U.S. Forest Service (unpublished data) had a long-term study of water quality in small wilderness lakes a few kilometers east of and at higher elevation than the lakes in my program. The U.S. Forest Service was concerned about the possible contamination of wilderness lakes from airborne pollutants emanating from the extensive development of oil and gas in the western part of the county. Their water samples were taken at depths of epilimnion and hypolimnion, and so they had measured temperature profiles at each sampling. The U.S. Forest Service kindly permitted me to analyze these data.

Their thermometer was at the end of a cable so that the maximum depth was at 24 m. Readings were made at intervals

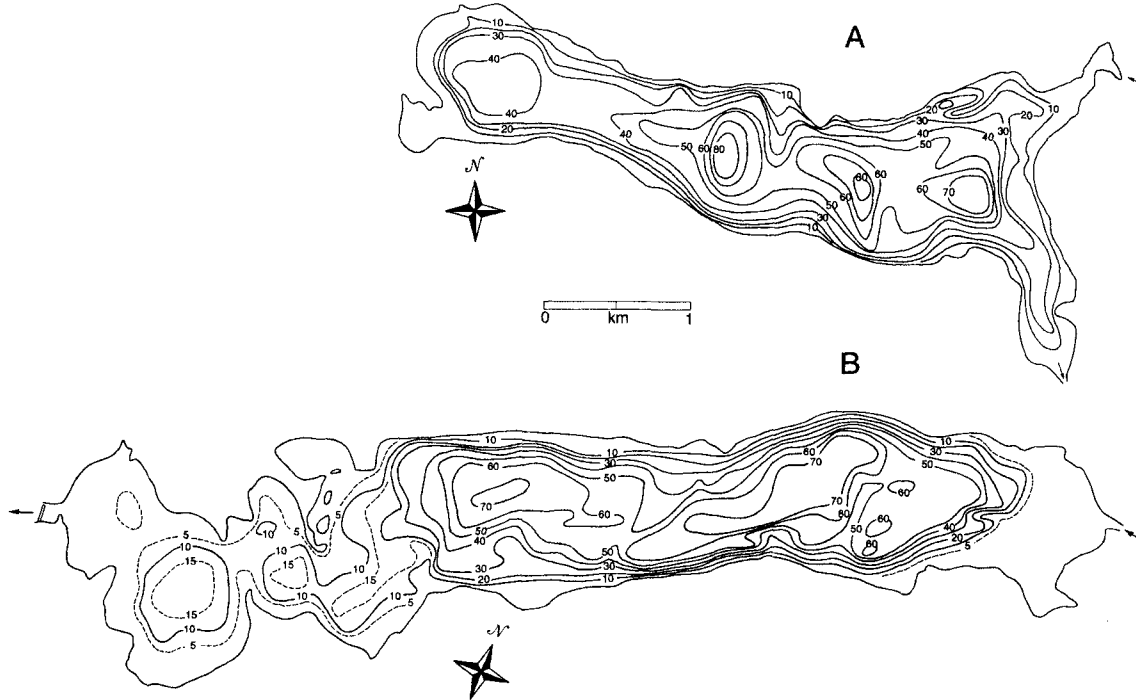


Fig. 1. Bathymetric maps, depth in meters. (A) Half Moon Lake, water surface elevation 2,316 m. (B) Boulder Lake, water surface elevation 2,222 m.

of 5 ft or sometimes 1 m, and the instrument was usually read to the nearest even degree C. The labor required to obtain these unique data was great. A small collapsible rubber boat was carried into the mountains on the backs of men and launched in rough and cold water and, in some seasons, in ice and snow. The water samples then were carried downhill in a pack, often on skis. Between July 1984 and August 1997, the U.S. Forest Service personnel measured 146 temperature profiles among five lakes in the Wind River Mountains. Together with my limited but more detailed data, some useful details of temperature characteristics of lakes of different sizes and elevations can be seen. The high elevation lakes are listed in Table 2.

The first three of these lakes are west of the continental divide in the Bridger Wilderness and the other two are on the east side in the Fitzpatrick and Popo Agie Wildernesses, respectively. All are at about the same elevation, $\approx 3,100$ m.

All of the lakes discussed here are temperate and dimictic in that they circulate twice a year, have large seasonal variation, and have surface temperatures above 4°C in summer and below that figure in winter.

The eight lakes are all glacial in origin and lie at relatively high elevations. All are isothermal near 4°C in winter and in summer

approach that temperature in the deep, relatively undisturbed region or hypolimnion. Yet there are modest differences among the temperature structures caused by differences in elevation, size, depth, and geographic location. The number of lakes and their measurements are sufficient to allow a tentative assessment of the effects of these differences.

Consider first the temperature profiles of all of the lakes at the same date in summer. In the total record, there is one short period, July 2 to August 2, for which a profile is available for all eight lakes (Fig. 2).

All of the lakes, large and small and at different elevations, are isothermal below the thermocline at a temperature approaching 4°C above freezing. The depth at which the water reaches this temperature is less in the small lakes, 11 to 15 m. Temperature of the largest lake, Fremont, reaches 4.5°C at 30 m and decreases below that depth. Fremont is essentially isothermal from 30 to 185 m, with the temperature decreasing slightly with depth, from 3.9°C to 3.7°C, owing to an increase in pressure.

Compared with the small higher-altitude lakes, the low-altitude, larger lakes had surface temperatures warmer by several degrees, thicker epilimnion, and steeper temperature gradients in the thermocline. The five high lakes had surface

Table 1. Large lakes in Sublette County, WY

Lake	Maximum depth, m	Area, km ²
Fremont	185	20
New Fork	62	5.0
Willow	85	7.3
Half Moon	85	4.3
Boulder	79	7.0

Table 2. Wilderness lakes for which temperature data are extant

Lake	Depth, m	Latitude	Longitude	Area, km ²
Hobbs	17	43 05 00 N	109 40 45 W	0.16
Deep	33	47 31 30 N	109 10 30 W	0.28
Black Joe	26	47 33 30 N	109 10 00 W	0.38
Ross	45	43 23 05 N	109 39 10 W	1.5
Saddlebag	22	42 36 36 N	108 57 23 W	0.20

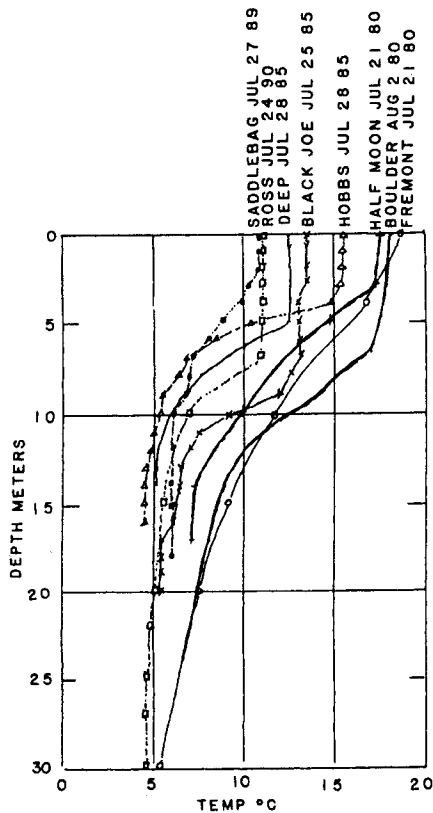


Fig. 2. Temperature profiles at about the same date in summer (late July) for the lakes studied, chosen from all of the available years of data.

temperatures between 11°C and 15.5°C, markedly colder than the 18°C measured in the larger lakes.

The difference in surface temperature at this date can be ascribed to the difference in elevation. The larger lakes are at an elevation of $\approx 2,200$ m, whereas at 3,100 m, the wilderness lakes have lower temperatures and deeper snow pack.

The thicker epilimnion in the large lakes can logically be expected as a result of longer fetch, which determines the magnitude of the waves and thus the depth of mixing. Long experience on the largest lake, Fremont, has shown me the violence of summer storms and associated waves that must mix the upper layers of water to greater depth.

The two lakes east of the continental divide, Ross and Saddlebag, are 2°C cooler than are the western counterparts, but the thickness of the mixed surface water is similar (Fig. 2). The eastern side of the Wind River Range has larger and more glaciers than does the western side and although there are not available comparative records, it is probable that snowfall is greater and temperature is somewhat lower than are found west of the continental divide. This disparity could account for the difference in lake surface temperature.

Using all of the years of record at one lake, a picture of the typical changes during the year can be seen. Figs. 3 and 4 present these data for the wilderness lakes. The mean temperature at Pinedale, Wyoming, is below freezing from November through March. The earliest observation of lake temperature usually was made in June and the last in October. The surface temperature generally increased until late July, and thereafter cooling began.

Fig. 3 shows the temperature profiles of Hobbs Lake from the end of June to the end of October. In 1985, on July 1, the surface temperature had warmed to 16°C, but the winter value of 5°C still persisted at 7 meters and below. Hobbs Lake continued to warm until July 10, and yet the epilimnion was still only 3 m in thickness. In August, cooling had occurred at the surface, but mixing was deeper, at 5 m, and the epilimnion was nearly isothermal at 15°C. This trend continued through the fall, and on October 11, 1989, the water was isothermal at 8°C to the full depth of the cable. By October 21, 1982, the whole body of water was isothermal at the temperature of 4°C. The winter isothermal

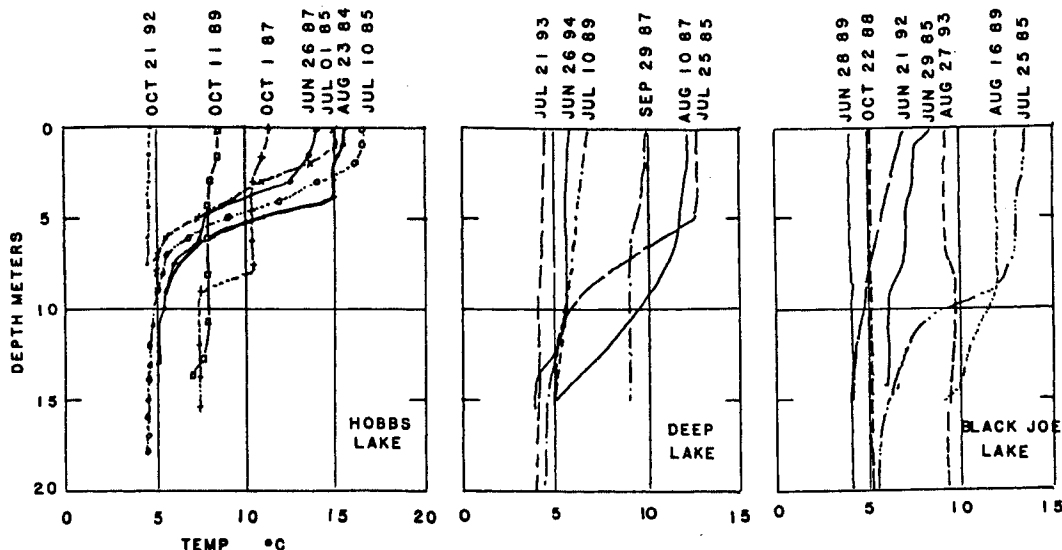


Fig. 3. Temperature profiles for three lakes west of the continental divide.

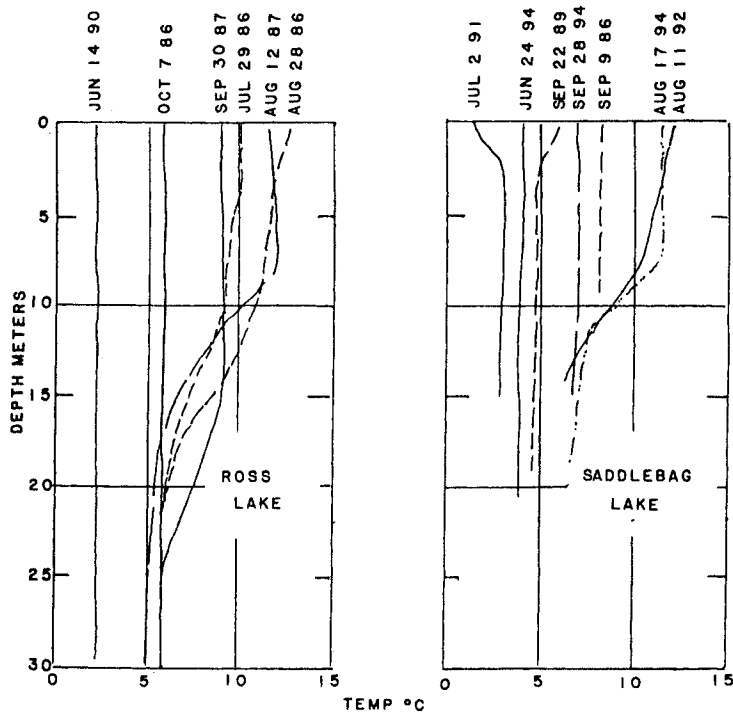


Fig. 4. Temperature profiles for two lakes east of the continental divide.

profile at 4°C persisted as late as July 21 at Deep Lake and June 28 at Black Joe Lake.

This sequence can be seen in all of the lakes. Surface warming but incomplete mixing continues until early August, when cooling begins accompanied by mixing to increasing depth. The profile becomes nearly isothermal at temperatures well above minimum, but the whole water column cools while maintaining its isothermal distribution until it reaches a temperature of 4°C. The development of stratification means the water body is very stable but as soon as the surface begins to cool, turnover begins as the heavier upper layer sinks.

In all these cases, the last profile of the fall season shows an isothermal condition at or close to maximum density, 4°C. In all three wilderness lakes discussed, the maximum depth of mixing before the profile becomes isothermal is between 10 and 14 m.

We turn now to the two lakes east of the continental divide, Ross and Saddlebag Lakes (Fig. 4). The data indicate that they are slightly colder than are their counterparts to the west, as mentioned earlier, although they are roughly the same in elevation. But Ross Lake is considerably larger than are the other wilderness lakes and is ≈20 m deeper. The greater size seems to

account for the thicker metalimnion and the deeper level of the top of the hypolimnion. The shape of the profile and the thickness of the mixed layer resemble the profiles of the large lakes at lower elevation. Ross Lake data include the only example of a winter isothermal profile at temperature below 5°C.

The data for the eight lakes studied suggest that the effect of lake size is greater than the effect of elevation, owing to wind having more ability to mix where the fetch is long. But the effect of changing air temperature as the seasons progress is remarkably similar in all of the lakes, regardless of size and elevation. The depth of mixing increases rapidly as the surface temperature decreases in late summer and fall.

Regardless of lake depth, the water below the thermocline tends to be isothermal slightly above freezing all of the way to the lake bed.

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1. Hutchinson, G. E. (1957) *A Treatise on Limnology* (Wiley, New York).
 2. Rickert, D. A. & Leopold, L. B. (1972) *U.S. Geological Survey Professional*

Paper 800 D (U.S. Government Printing Office, Washington, DC), pp. 173-188.
 3. Leopold, Luna B. (1980) *Proc. Natl. Acad. Sci. USA* 77, 1754-1758.