METHOD OF EVALUATING TEMPERATURE IN LAKES WITH DESCRIPTION OF THERMAL CHARACTERISTICS OF CONVICT LAKE, CALIFORNIA

BY NORMAN REIMERS AND BOBBY D. COMBS

FISHERY BULLETIN 105

UNITED STATES DEPARTMENT OF THE INTERIOR, Douglas McKay, *Secretary*
FISH AND WILDLIFE SERVICE, John L. Farley, *Director*

ABSTRACT

Two years of temperature observations at Convict Lake, a 168-acre alpine lake in eastern California, are used as the basis for a description of thermal characteristics including annual temperature cycle, distribution of temperature, and thermal stratification in relation to morphometry and weather. The heat-budget method of assessing heat in lakes has inherent limitations on lake size, depth, and geographical location that restrict its usefulness to general comparisons among large bodies of water. The method of measuring sustained heat intensity (temperature summation) presented here is free of these limitations. Data developed from temperatures of Convict Lake and other lakes of the same drainage basin support the conclusion that such a method can be serviceable for comparing lakes of various sizes and situations over selected periods of time, or for evaluating temperature in relation to other measures of lake productivity. A summation procedure is suggested in which the base temperature is 32° F. and the summation units are day-degrees in excess of the base.

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By NORMAN REIMERS and BOBBY D. COMBS, *Fishery Research Biologists*

One phase of productivity studies on the alpine lakes of Convict Creek Basin, Mono County, Calif., concerns the relation between aquatic productivity and available heat. The investigation of this relationship requires temperature data in a form that will permit thermal comparisons among lakes of various sizes and depths over selected periods of time, and that is also adaptable to problems of association between temperature and measurable production. A method of thermal comparison for alpine lakes should permit annual comparisons among lakes that can be observed the year round and short-term comparisons among lakes whose seasonal accessibility is limited.

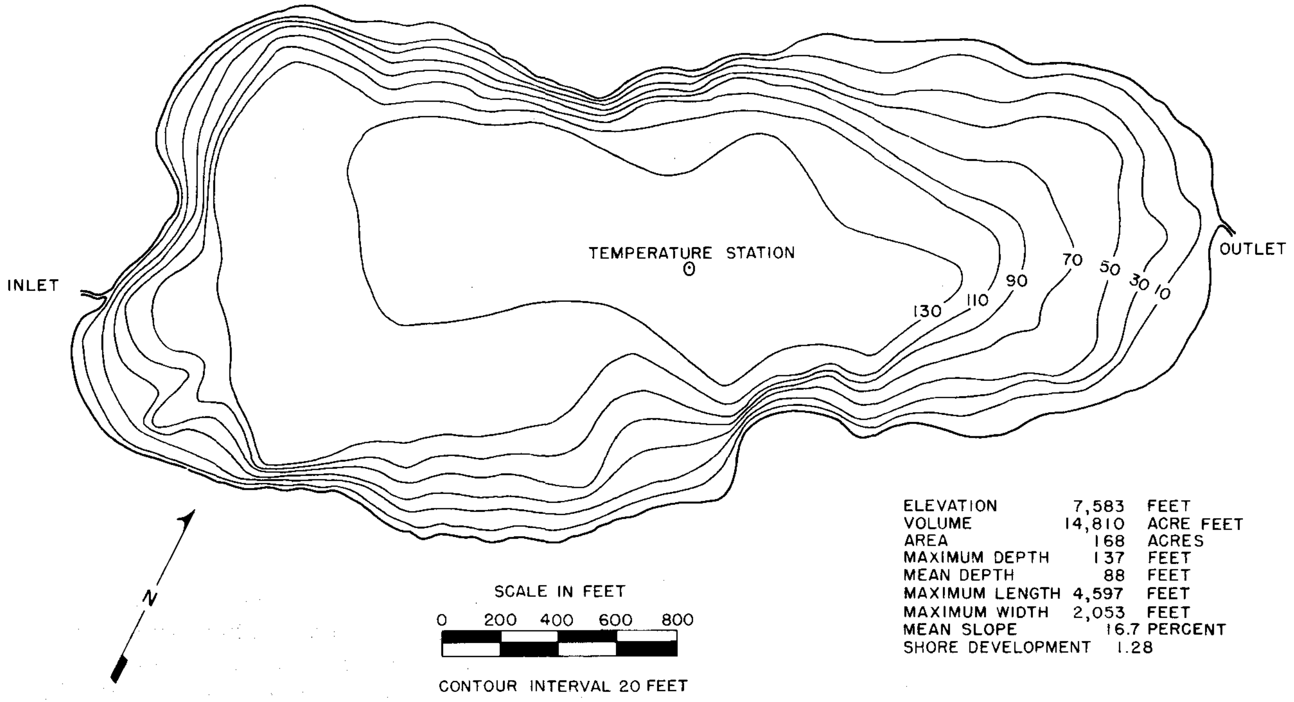
This report presents an analysis of 2 years of temperature observations on Convict Lake, the lowermost lake in the Convict Creek Basin and the only one accessible throughout the year. Its purposes are to initiate a record of temperature cycles in alpine Sierra Nevada lakes of moderate size and to introduce a method of temperature summation that fulfills the above requirements and that may be useful for thermal comparisons involving other lakes of various sizes and locations.

The work was conducted from the United States Fish and Wildlife Service Convict Creek Station, located 2½ miles downstream and 5 miles by road from the lake. During the open season, transportation was by light truck and small boat. In winter, the lake was reached by ski or snowshoes, and temperatures were measured through the ice. The period of regular observations extended from May 1951 to May 1953, with a weekly schedule maintained when possible. Weather and ice conditions during the first winter resulted in a 2-month gap in the data, and the interval between observations was lengthened several other times because of storms. In all, 85 vertical temperature series were recorded during the study.

THE LAKE AND ITS WATER SUPPLY

Convict Lake is slightly less than a mile long, is 2,053 feet wide (maximum), and has a surface area of 168 acres and a volume of 14,810 acre-feet. More than half the surface area falls within the 100-foot contour, and a large central section approaches the maximum depth of 137 feet. Additional morphometric data are tabulated on the hydrographic map (fig. 1). In general, slope and bottom conditions are similar to those of many other glacial lakes of comparable size in the eastern Sierra Nevada. Prominent physical features of such lakes are low shore development, simple basins, abrupt shores, and a small percentage of shoal area. Convict Lake is situated at the foot of a steep, rocky canyon and is flanked by bedrock ridges and extensive glacial moraines. Although it appears to be sheltered on nearly all sides by steep slopes, the lake is fully exposed to frequent strong winds which funnel down the canyon from above. Its elevation (7,583 feet) subtracted from that of the nearest tributary lake (Mildred: 9,900 feet) gives a fall in the drainage of 2,317 feet in a little less than 3 miles (U. S. Geological Survey, datum 1934; Mount Morrison Quadrangle). Additional geographical and geological details may be obtained from the general report on the lakes of the basin (Reimers, Maciolek, and Pister, 1955).

The water supply consists almost entirely of melted snow from higher parts of the drainage. Convict Creek, the only tributary stream, enters the lake at its south end and continues from the north end to join an impoundment of the Owens River. Mean monthly discharges from Convict Lake varied from 8.3 to 50 cubic feet per second in 1951, and from 10.7 to 97.9 cubic feet per second in 1952. Records are from a gaging station located 1 mile below the lake and maintained by the



ELEVATION	7,583	FEET
VOLUME	14,810	ACRE FEET
AREA	168	ACRES
MAXIMUM DEPTH	137	FEET
MEAN DEPTH	88	FEET
MAXIMUM LENGTH	4,597	FEET
MAXIMUM WIDTH	2,053	FEET
MEAN SLOPE	16.7	PERCENT
SHORE DEVELOPMENT	1.28	

FIGURE 1.—Hydrographic map of Convict Lake, Calif.

City of Los Angeles Department of Water and Power. Seepage and springs account for a small fraction of the water entering the lake. Computations based on discharge records for several years indicate that average flows would produce a volume of water sufficient for a complete exchange of the lake water once in each 9 months.

NATURE OF THE OBSERVATIONS

Observations were made at a single station over the deepest part of the lake that coincided approximately with the center of oscillation. Because of the single, extended depression and slight shore development (fig. 1), vertical temperature series taken at this point were sufficient to characterize the lake without additional shallow-water observations. Water temperatures were measured at 10-foot intervals beginning at the surface, and air temperatures were taken in the shade 2 feet above the surface. A Foxboro resistance thermometer with 0.5° F. graduations was used for all temperature observations at the lake. A continuous air-temperature record was maintained at Convict Creek Station with a Taylor recording thermometer of 0.5° accuracy. These temperatures, which on a yearly basis were found to agree closely with those recorded at the lake, have been used to some extent in judging the effects of winter weather on heating of the lake.

CLIMATE AND THE GENERAL TEMPERATURE CYCLE

The eastern slope of the Sierras in the vicinity of Convict Lake is a moisture-deficient, sagebrush-covered upland where most of the precipitation occurs as snow during the winter. Daily air-temperature maxima usually range from 60° to 85° F. in summer, but occasionally reach 90°. Humidity is low in spring, summer, and fall because of the moisture-removing effect of the high mountains on easterly moving air masses. The primary influence on winter conditions in the area is the nature of a succession of Pacific storms, and winters vary accordingly in length and severity. The winter of 1950–51, preceding the first year of the Convict Lake observations, was relatively mild as noted by Maciolek and Needham (1952). Prolonged periods of cold weather did not occur, and ice cover on the lake was intermittent and light. The 2 years of observations fortunately included an average winter and one of the most severe winters on record. In 1951–52, snowstorms kept the ground covered from November 18 to mid-April, and permanent ice was present on the lake from December 20 until the end of April, reaching a maximum thickness of 22 inches. In 1952–53, snowfall was relatively light, with the ice cover intermittent and reaching a thickness of only 4 inches. Although the mean air temperature of the period May 1951 to May 1952 was only 2.9° lower than that of the following 12-month period (41° and 43.9° F.), the first year contained 3,372 hours below freezing as compared with 2,750 such hours between May 1952 and May 1953 (table 1). The effects of a cold winter on subsequent heating of the lake are discussed under mean temperatures.

TABLE 1.—*Air temperatures at Convict Creek Station by months, May 1951 to April 1953*

[In degrees Fahrenheit]

Month	Monthly temperatures			Temperature range		Number of hours—	
	Mean maximum	Mean minimum	Mean	Maximum	Minimum	Above 32°	Below 32°
1951–52							
May	67.7	32.4	50.5	87	17	651	93
June	78.1	38.5	58.3	87.5	27	705	15
July	81.5	46.1	63.8	86	29	742	2
Aug	77.8	41.2	59.5	86	32.5	744	0
Sept	76.9	36.7	56.8	83.5	29	712	8
Oct	62.2	25.7	44	72.5	14	528	216
Nov	49.3	16.7	33	67.5	−8	308	412
Dec	28.9	10.3	19.6	42	−19	58	686
Jan	27.6	9.6	18.6	47.5	−12	36	708
Feb	35.8	8.3	22.5	45	−5	121	551
Mar	39.2	11.4	25.3	49	−5	277	467
Apr	55.3	26	39.8	69	15.5	506	214
Mean and total			41			5,388	3,372
1952–53							
May	70.3	32.1	51.2	82.	23	689	55
June	75.3	36.6	56	85	22	689	31
July	82.1	44.5	63.3	88.5	35	744	0
Aug	80.1	40.7	60.4	83.5	35.5	744	0
Sept	71.8	36.6	54.2	83	26	688	32
Oct	69.6	27.5	48.5	76	18.5	559	185
Nov	44.8	13.4	29.1	63	0	197	523
Dec	33.4	11.5	22.4	42.5	−8	72	672
Jan	43.1	19	31	52	4	361	383
Feb	47.8	24.7	31.3	57.5	5	270	402
Mar	54.5	19.2	36.9	66	0	425	319
Apr	60.9	24.6	42.8	82	3.5	572	148
Mean and total			43.9			6,010	2,750

The most notable aspect of the weather as it affects Convict Lake is the wind that sweeps the lake almost daily and varies from gusty breezes to prolonged gales that attain velocities of more than 70 miles an hour. Strong winds are especially frequent between October and May, when their action is the one factor that delays or, in mild years, prevents formation of a permanent ice cover. On several occasions in late 1952 the lake was cleared of 2 to 3 inches of ice in a few hours. Wind action is also of controlling importance in summer heat distribution, maintaining the lower limit of the epilimnion at roughly one-quarter to one-half the depth of the lake between July and October, and contributing to the weak and fluctuating nature of the thermocline.

In general, warming of the upper strata proceeds slowly until May, rapidly in late May and June, and more slowly again in July. Peak temperatures of the upper 20 feet are reached during August coincident with highest mean temperatures. Recognizable stratification developed in early July of 1951, following what may be regarded as a normal winter and spring. In 1952, after a heavy winter with resulting increased runoff, stratification was delayed until August. Owing to the constancy of wind agitation, much of the heat absorbed in early summer is transferred to the depths, overcoming the incipient thermal barrier, and the resulting lag in heat storage by the epilimnion places a short time limit on a stratified condition in any year. By the time the epilimnion nears the point of maximum heat, when sharply defined stratification is possible, the lake as a whole is about to lose heat.

Heat loss, as indicated by mean temperature, begins about the third week in August. Cooling becomes rapid in late October or early November, particularly in the upper strata. In this condition, there is only a small temperature decline with depth and little resistance to circulation. A drop in temperature of the upper strata, accompanied by a rise in temperature below 80 feet (table 2: Oct. 16 and 25, 1951), indicates that preliminary deep mixing occurs as early as mid-October, followed by stabilization and further cooling. Autumn overturns were recorded on November 30, 1951 (43.5° F.) and on December 4, 1952 (42.5° F.), but it may be noted from the temperature series preceding these dates (tables 2 and 3) that a homothermous condition at slightly higher temperatures could have been present several days earlier. Complete circulation begins with homothermy and continues until the lake

TABLE 2.—*Temperature readings at Convict Lake, May 7, 1951 to April 1, 1952*

[In degrees Fahrenheit]

Date	Air temperature	Water temperature at depth (feet) of—													
		0	10	20	30	40	50	60	70	80	90	100	110	120	130
1951															
May 7	58	45.5	44	43.5	43.5	43.5	43	43	43	42.5	42.5	42	42	42	42
14	53.5	46	45	44.5	44.5	44.5	44.5	44	43.5	43.5	43.5	43	43	42.5	42.5
21	59.5	50.5	50	48	47	46	45.5	44	44	43.5	43.5	43	43	43	43
28	70.5	56	53	52	50.5	49.5	47	46	45.5	44	44	43.5	43.5	43.5	43
June 4	60	53	52.5	51	50.5	49.5	48	46.5	45.5	44.5	44	43.5	43.5	43.5	43
11	64.5	54	52	51.5	50	49.5	48	47	45.5	44.5	44	43.5	43.5	43.5	43
14	69.5	58	55	53	52	50.5	48.5	46	45	44.5	44	43.5	43	43	43
18	69.5	58.5	56	53.5	52	49.5	48.5	47	45.5	44.5	44	43.5	43	43.	43
25	58.5	58	56	54	52.5	51.5	48.5	46.5	45	44	43.5	43	43	43	43
July 2	71	60.5	59.5	59.5	57	53.5	50	47	46	44.5	44.5	44	43	43	43
9	70	63.5	61	59	57.5	55 5	53	47	46	45	44.5	44	43	43	43
16	66	62.5	61.5	58.5	56	54	52	47	46	45.5	44.5	44	43	43	43
23	74.5	67	63	61	59.5	54	51.5	48.5	47	46	45	44.5	44.5	44	44
30	72	64	63.5	61.5	60.5	57	53	49	47	45	44.5	44	43	43	43
Aug. 6	66	63	62.5	62	61	57	53	49.5	48	46	45	44.5	44	43	43
13	74	63	63	62.5	60	51.5	48.5	46.5	45	44.5	44	43.5	43.5	43.5	43.5
21	62	62	61.5	61.5	61	58.5	52	49	47.5	46.5	45.5	45	45	44	44
28	62	60.5	60.5	60.5	60	59.5	53.5	48.5	47	46	45	44.5	44.	43.5	43.5
Sept. 4	68	61	60.5	60	59.5	59	55.5	49	47.5	46	45	44	43.5	43.5	43.5
11	65	61.5	60	59.5	59.5	59	56.5	49	47	46	45	44.5	44	44	44
18	63.5	61	61	61	60.5	60	59	53	48.5	46.5	45.5	44.5	44.5	44	44
25	62.5	59.5	59.5	59	59	59	58	51.5	48	46.5	45	44.5	44	44	44
Oct. 2	54	57	56	56	56	56	56	56	49.5	47	46	45	43.5	43.5	43.5
9	69.5	56.5	55.5	55.5	55.5	55.5	55.5	55.5	49.5	47.5	46.5	45.5	44.5	44	43.5
16	57.5	52.5	52.5	52.5	52.5	52.5	52	52	52	48	45.5	44	44	43.5	43.5
25	36	49.5	49.5	49.5	49	49	49	49	49	49	49	47.5	46.5	45	45
31	53	49	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48	48	48	45.5	44.5	44
Nov. 2	53.5	51	50	49.5	49	49	49	49	49	49	49	48.5	46.5	45.5	45
9	49.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48.5	48	47	44.5	44.5
16	52	46	46	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5
23	23	44.5	44.5	44.5	44.5	44	44	44	44	44	44	44	44	44	44
30	52.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5	43.5
Dec. 7	22.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5	40.5
14	39	40	40	40	40	40	40	40	40	40	40	40	40	40	40
1952															
Feb. 6	45	33	36	36	36	36	36	36	36	36	36	36.5	36.5	36.5	36.5
14	39	33	36	36	36	36	36	36	36	36.5	36.5	36.5	36.5	36.5	36.5
21	37	32.5	35.5	36	36	36	36	36	36	36	36	36	36	36.5	36.5
Mar. 11	25.5	32	36	36	36	36	36	36	36	36	36	36	36	36	36
25	53	32	36	36	36	36	36	36	36	36	36	36.5	36.5	36.5	36.5
Apr. 1	49.5	32	36	36	36	36	36	36	36	36	36	36	36	36	36.5

has cooled uniformly to 39° F. or lower and surface ice has formed. If the ice is intermittent, circulation is maintained during periods of open water throughout the winter and spring at temperatures as low as 36° F.

The temperature series for March and April 1953 (table 3) show that warming of the lake in an ice-free spring was gradual and uniform up to about 40° F., at which point the warming of surface layers began to accelerate. Circulation during the early spring warmup of 1953 was thus almost continuous and no actual overturn occurred. In 1952, the late ice disappeared in the last week of April. By May 9, the earliest observation date in 1952, temperatures of deeper strata had risen 4° since April 1 (indicating some heating through the ice), and the surface had begun to warm additionally. It is likely that complete and thorough mixing occurs almost immediately after the breakup of permanent winter ice, and that the period of spring circulation at such a time is short, a week at the most.

DISTRIBUTION OF TEMPERATURE

SURFACE TEMPERATURES

Extremes of 32° F. (under ice) and 67° F. (at the surface) were recorded during the 2 years. The higher maximum occurred on July 23, 1951, following a mild winter and spring. The surface maximum of 1952, following a severe winter and late spring, was 3 weeks to a month later (August 16–21) and considerably lower (60° F.). The most rapid increases in surface temperature for both years were in late May, even though this is a period when mixing to a considerable depth is still in progress and insolation has not yet reached its full intensity. Increases were then gradual through June, and the data indicate that in a "normal" year the surface remains above 60° F. through the months of July, August, and Sep-

TABLE 3.—*Temperature readings at Convict Lake, May 9, 1952 to May 10, 1953*

[In degrees Fahrenheit]

Date	Air temperature	Water temperature at depth (feet) of—													
		0	10	20	30	40	50	60	70	80	90	100	110	120	130
1952															
May 9	55	42.5	42	41.5	41	41	41	41	40.5	40.5	40.5	40.5	40.5	40.5	40.5
16	49	44.5	44	44	44	42.5	42.5	42	41.5	41.5	41.5	41	40.5	40.5	40.5
23	58	48	45	44.5	44	43.5	43	42.5	42.5	42	42	41.5	41.5	41.5	41.5
29	60	50	48	47	45	44.5	44.5	44	43	42.5	42	42	42	42	41.5
June 6	60.5	51.5	49.5	48.5	47.5	47	46	45	43.5	42.5	42	42	42	41.5	41.5
16	62	49.5	47.5	47	46.5	46	45.5	45	44.5	44	43.5	43	43	42.5	42
24	57.5	49	49	48.5	48	47	47	45.5	45	44	43.5	43	43	43	42.5
July 1	69.5	52.5	50	49.5	48.5	48	47	46	45.5	45	44	43.5	43	43	43
9	64.5	53	52.5	51.5	50	48.5	47.5	46.5	45	45	43.5	43.5	43	43	43
16	61.5	56	53.5	52	51.5	50	49.5	47	45.5	45	44.5	44	44	43.5	43.5
23	75.5	58	56	55	54	52	50.5	48.5	46.5	46	45	44.5	44	43.5	43.5
30	58	57	56	55	54	53	49	47.5	46 5	45.5	44.5	44	44	43.5	43.5
Aug. 6	72.5	58	57	55.5	54.5	54	51	48.5	47	46	45.5	44.5	44	43.5	43.5
13	74	60	58.5	57	56.5	55.5	53	50.5	47.5	45.5	45	44.5	44	44	44
21	68	60	59.5	59	58	57	53	49.5	47.5	47	46	45.5	45	45	44.5
28	63.5	58	57.5	57	57	56.5	55	50	47.5	46.5	45.5	44.5	44.5	44	44
Sept. 5	58	57	57	57	57	56.5	54.5	50.5	49	47.5	45.5	44.5	44.5	44.5	44.5
10	42	55.5	55.5	55.5	55.5	55.5	54.5	53.5	48	46.5	45.5	45	44.5	44	44
17	67	56	55.5	55	55	54.5	54	54	49	47.5	46	45.5	44.5	44.5	44.5
26	62	55	55	55	55	55	54.5	54	52.5	46.5	46	44.5	44	44	44
Oct. 3	72	56	55	55	55	54.5	54	53.5	50.5	48	46	45	44	44	44
9	60.5	55.5	55	55	55	55	54.5	53.5	51	47.5	46	45	44.5	44	44
16	66	55.5	55	55	54.5	54.5	54.5	54	51	47.5	46.5	45.5	45	44	44
23	62.5	55	54	54	54	54	53.5	53.5	52.5	48	46	45	44.5	44.5	44
30	56.5	53	52.5	52.5	52.5	52.5	52.5	52.5	52	47.5	46	45	44	44	43.5
Nov. 7	46	51	51	51	51	51	51	51	51	50.5	46.5	45	44.5	44	44
18	36	46.5	46.5	46.5	46.5	46.5	46.5	46	46	46	46	46	46	44.5	43.5
24	43.5	45	45	45	45	45	44.5	44.5	44.5	44.5	44.5	44.5	44.5	44.5	44.5
Dec. 4	27	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5	42.5
11	36.5	39.5	40	40	40	40	40	40	40	40	40	40	40	40	40
17	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
23	27.5	39	39	39	39	39	39	39	39	39	39	39	39	39	39
1953															
Jan. 12	44	37	37	37	37	37	37	37	37	37	37	37	37	37	37
19	43	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5
30	52	36	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5
Feb. 11	47	34.5	35.5	36	36	36	36	36.5	36.5	36.5	36.5	36.5	36.5	36.5	36.5
19	34.5	35.5	36	36	36	36	36	36	36	36	36	36	36	36	36
Mar. 6	41	33.5	37	37	37	37	37	37	37	37	37	37.5	37.5	37.5	37.5
11	33.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5
31	50	39	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5
Apr. 8	35	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5
15	55.5	41.5	40.5	40.5	40	40	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5	39.5
22	53	42.5	41	41	41	41	41	41	40.5	40.5	40.5	40.5	40.5	40.5	40.5
May 2	48	42.5	42	41.5	41.5	41.5	41.5	41.5	41.5	41.5	41.5	41.5	41.5	41	41
10	38.5	43	43	43	43	43	43	42	42	42	42	42	42	41.5	41.5

tember. Rapid decline of surface temperatures began about October 9 in 1951 and near the end of October in 1952. A clear connection between surface and air temperatures at these times is indicated in tables 2 and 3. The continuation of surface cooling may be followed on figures 2 and 3, which were constructed to illustrate the seasonal variation of surface-to-bottom temperature ranges. Four weeks in 1952 and six weeks in 1951 were required to reduce the October surface temperatures from the beginning of rapid decline to 45° F., at which point the lake was essentially homothermous.

Although surface temperatures near the shore on calm days were sometimes found to be 1° or 2° higher than at the central station, the volume of shallow water involved is slight and the duration of calmness is usually brief. Water between the shoreline and a depth of 10 feet, which during favorable weather might be expected to attain slightly higher temperatures than the upper 10 feet at a distance from shore, amounts to less than 1 percent of the total lake volume. Vertical temperature series taken at a depth of 30 feet agreed regularly with the upper 30 feet of midlake temperatures. It is therefore evident that the entire lake may be considered as open water, and that wind action and the complete absence of sheltered shallow areas preclude any significant addition to surface heating from inshore areas.

DEEP TEMPERATURES

The seasonal course of temperatures at 130 feet, reported here as bottom temperatures, may be followed in tables 2 and 3 and on figures 2 and 3. Temperatures at this depth are affected very

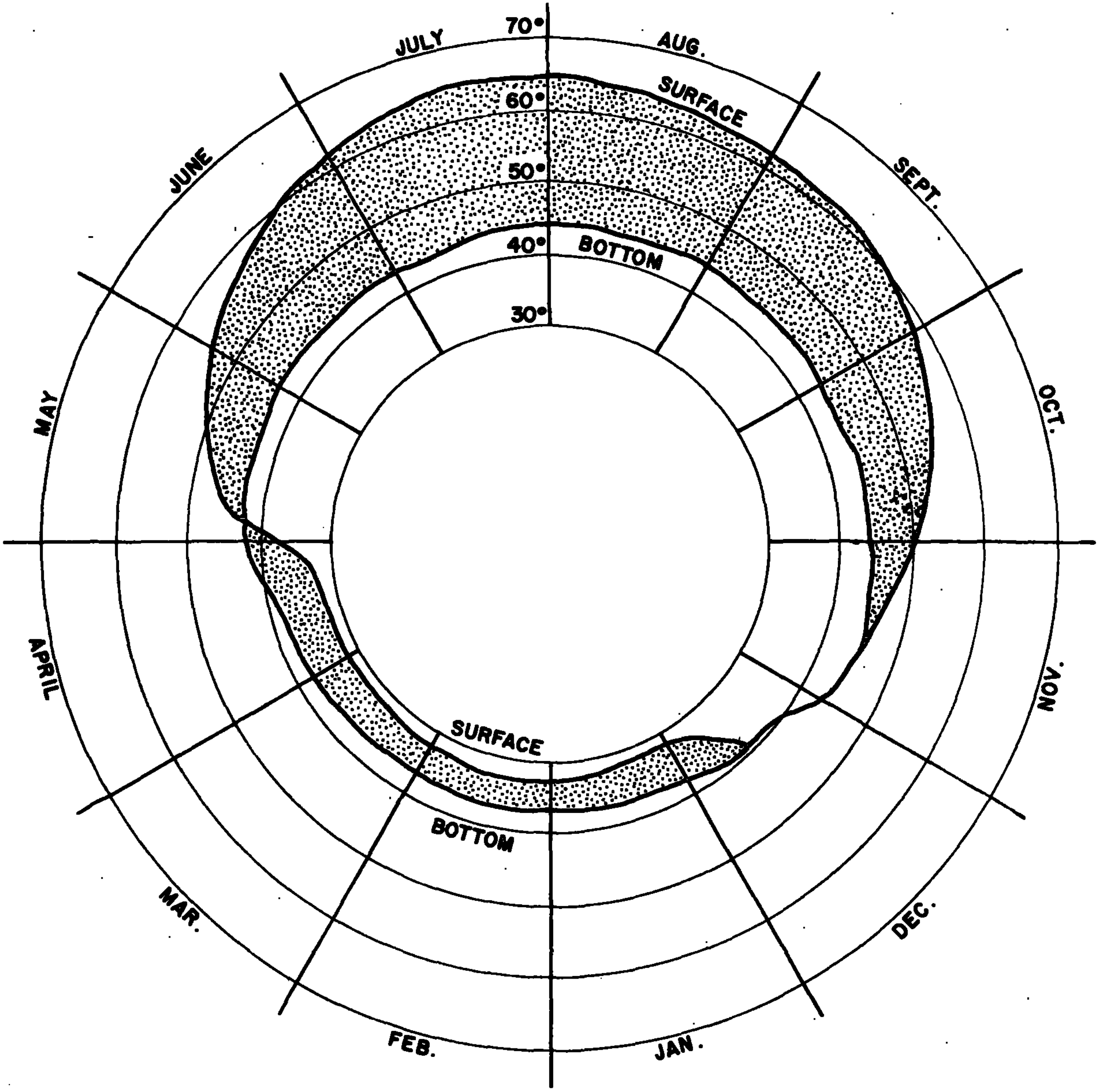


FIGURE 2.—Annual temperature cycle in Convict Lake, Calif., May 1951 to May 1952. (Temperatures in degrees Fahrenheit.)

little during the warming period, reaching a level of 40° to 43° F. in the spring circulation and rising only 2° to 4° through the summer and fall. Maximum bottom temperatures are attained at the beginning of complete autumn circulation, and are therefore brought about by cooling and mixing rather than by heating and mixing, as in upper and mid-depth zones. A seasonal range of temperature almost as narrow as that at the bottom is found through a hypolimnetic zone extending from the bottom to a depth of about 90 feet (tables 2 and 3). Above 90 feet, the effects of thermal stratification and occasional deep mixing are more pronounced, with the yearly temperature range of each stratum increasing steadily toward the surface.

MEAN TEMPERATURES

The best indication of time and degree of heat gains and losses attributable to yearly

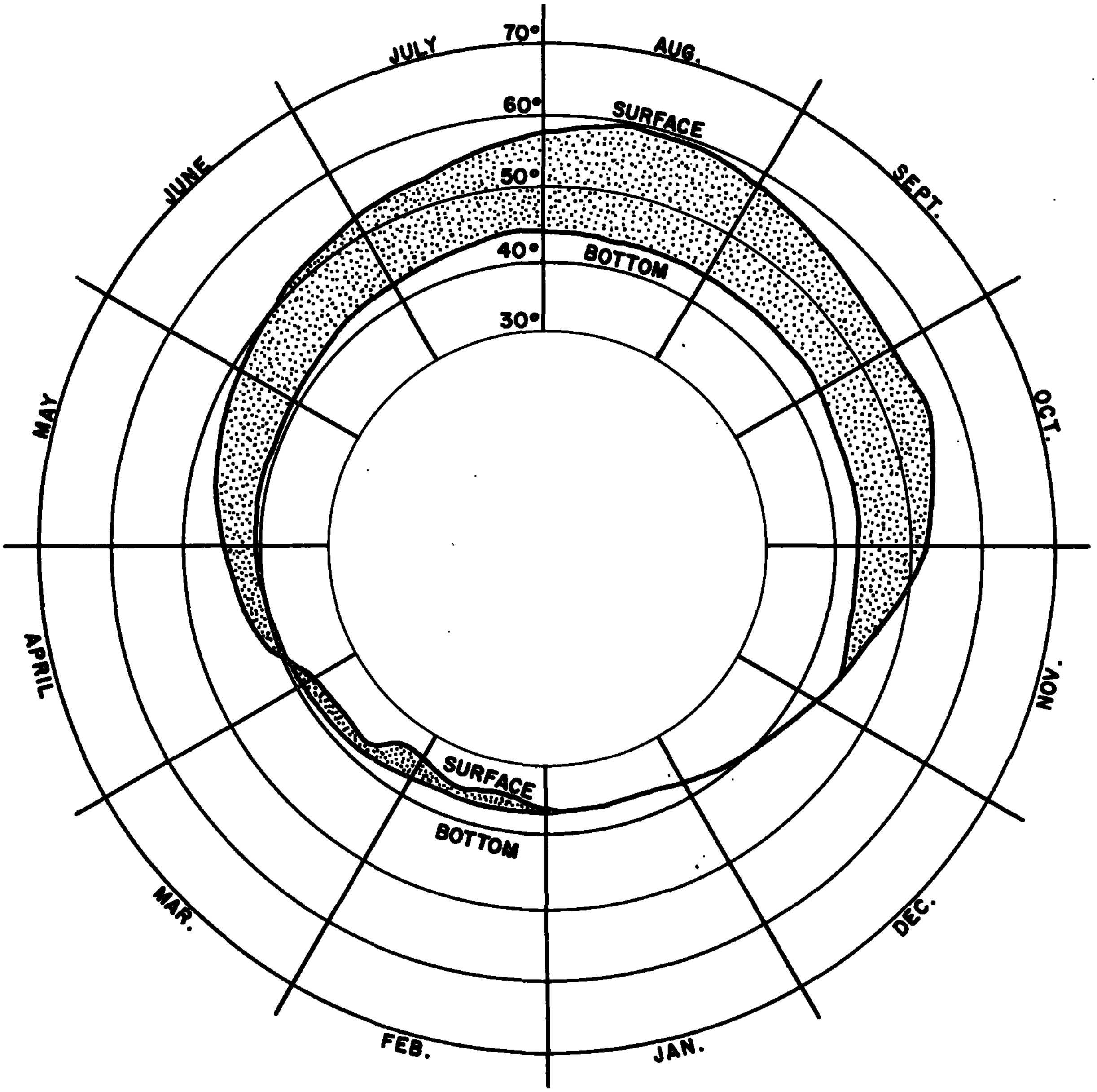


FIGURE 3.—Annual temperature cycle in Convict Lake, Calif., May 1952 to May 1953. (Temperatures in degrees Fahrenheit.)

weather, and of the probable average course of events, is found in the mean-temperature record. Table 4 lists the mean lake temperatures, calculated by 20-foot strata, for all observation dates. Figure 4 graphs the same data (smoothed by running averages of 3) for essential parts of 1951 and 1952, which followed radically different winter weather and ice conditions as previously noted, and for the first 4 months of 1953. The 1951–52 curve between April 1 and May 9 was extrapolated in two segments by estimate because it is certain that heating of the lake was somewhat slower under the ice than after the ice had broken up near the end of April. The figure demonstrates that in 1952, following a severe winter, heating of the lake as a whole lagged as much as a month behind the preceding year, and that for any given date between May 10 and October 5 the mean temperature was 1° to 4° lower than in the preceding year.

TABLE 4.—*Mean temperatures at Convict Lake, May 7, 1951 to May 10, 1953*

[In degrees Fahrenheit; by 20-ft. strata]

Date of observation	Mean temperature	Date of observation	Mean temperature
1951		*1952*—Con.	
May 7	43.2	May 9	41.2
14	44.1	16	42.6
21	45.7	23	43.5
28	48	29	44.8
June 4	48	June 6	45.7
11	48	16	45.5
14	48.7	24	46
18	48.7	July 1	46.9
25	48.9	9	47.7
July 2	50.9	16	48.6
9	51.6	23	50.2
16	51.1	30	50
23	52.7	Aug. 6	50.7
30	52.9	13	51.7
Aug. 6	53.1	21	52.5
13	53.6	28	51.6
21	53.4	Sept. 5	51.8
28	52.9	10	51.7
Sept. 4	52.7	17	51.6
11	52.7	26	51.4
18	53.6	Oct. 3	51.7
25	52.9	9	51.5
Oct. 2	52.3	16	51.5
9	52.2	23	51.4
16	50	30	50.2
25	48.6	Nov. 7	49.8
31	48	18	46.1
Nov. 2	48.7	24	44.8
9	48	Dec. 4	42.6
16	45.5	11	40.1
23	44.1	17	40.1
30	43.5	23	39
Dec. 7	40.5		
14	40.1	*1953*	
1952		Jan. 12	37
		19	36.5
Feb. 6	35.8	30	36.4
14	35.8	Feb. 11	36.1
21	35.6	19	36
Mar. 11	35.6	Mar. 6	36.7
25	35.6	11	37.6
Apr. 1	35.6	31	39.5
		Apr. 8	39.6
		15	40.1
		22	40.9
		May 2	41.6
		10	42.4

General observations during March and April for 4 years (1951–54) indicate that a permanent ice cover may be present on the lake in March, but is definitely unusual in April. The normal course of spring heating is therefore believed to be similar to that shown for 1951 and 1953 in figure 4. On this basis, the daily gain after the disappearance of ice varies between 0.07° and 0.30° F. per day, with the most rapid rise in late May. The coarse average rise in mean temperature for the entire warming period (from a winter mean of 36° F.) is about 0.85° F. per week, and the highest summer mean is reached some time in August. The highest mean temperatures of 1951 and 1952 were 53.6° and 52.5° F. The mean temperature was above 50° for 15 weeks in 1951, and for 14 weeks in 1952. The average mean temperatures for these two periods were 52.5° and 51.3° F.

STRATIFICATION

Wind circulation and the inflow of cold water combine to prevent the formation of a sharp and well-sustained thermocline (1° C. per meter, or 0.549° F. per foot) in Convict Lake, but the three primary temperature regions nevertheless develop and remain distinct for 1 to 3 months of each year. Selected temperature series for 1951 and 1952, spaced 1 to 2 weeks apart, have been plotted (fig. 5), and illustrate the progress of stratification. On these charts, the temperature scale of each gradient is indicated at its point of origin (bottom) and termination (top). The points of origin of gradients are also time scaled to maintain the proper spacing of dates. Although the overlapping temperature scales and changing shapes of temperature gradients produce a slight horizontal distortion, the general movements of the thermocline can be followed clearly. In 1951, a thermocline was present as shown in the shaded area of the figure. Its thickness, though masked somewhat by the large depth interval of observations, was never greater than 15 feet, and the considerable depth of its first formation (50 feet) is a good indication of the extent of wind-mixing interference. Near the end of July 1951, the thermocline appears to have been overcome by a deeper mixing and to have re-formed shortly thereafter.

In 1952, an unusually large runoff strongly influenced summer thermal characteristics; as the inflow was several degrees colder than the epilimnial water of the lake. Stratification was weaker than in the preceding year, and a true thermocline was in existence only during the month of September, at depths ranging from 60 to 80 feet. The development of stratification in the 2 years is best illustrated by the seasonal progress of isotherms (figs. 6 and 7). In 1951, the rapid heat gains and regular development of strata are shown by closely spaced, parallel-tending isotherms. In 1952, the influence of colder water is evident in irregularly spaced and frequently divergent isotherms. The average summer condition would be a thick epilimnion and a slightly thicker hypolimnion, which account for over 90 percent of the depth of the lake and are separated by a thin, occasionally penetrable thermocline. With the progress of rapid autumn cooling, the already weakened thermocline follows the usual down-

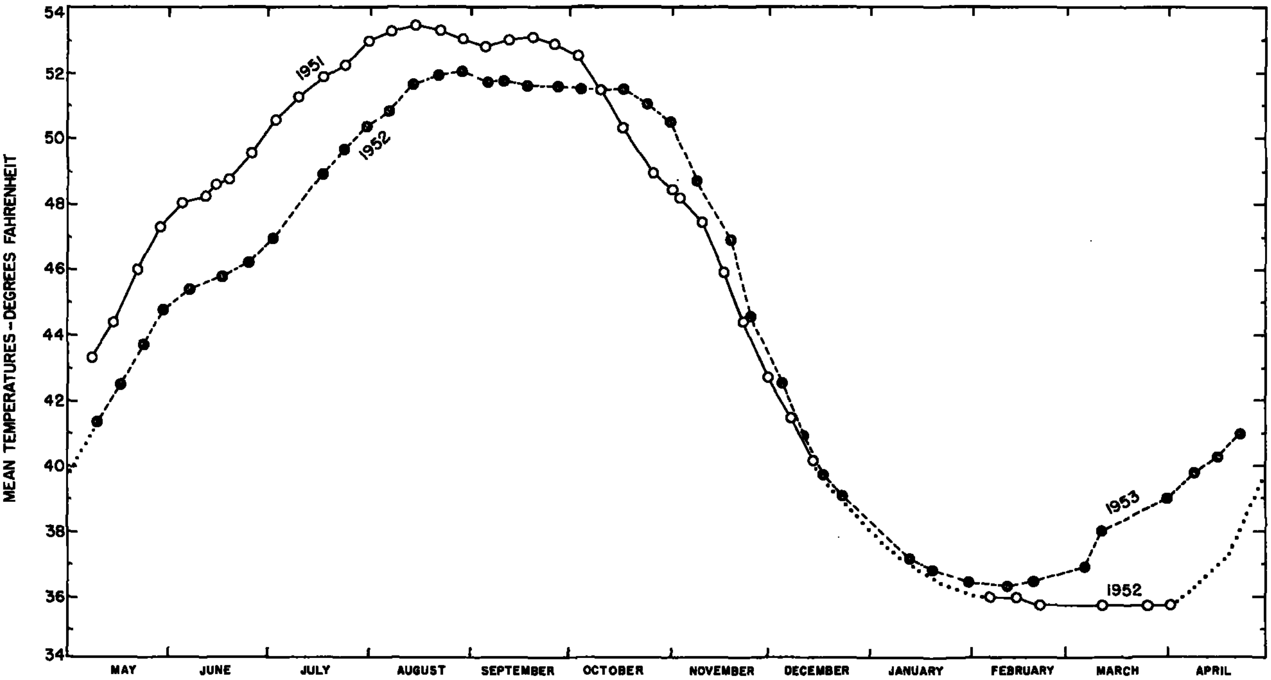


FIGURE 4.—Seasonal variation in the mean temperatures of Convict Lake, Calif., compared for 2 years, May 7, 1951 to May 10, 1953. Data were smoothed by running averages of 3 (open dots, 1951–52; solid dots, 1952–53).

ward course and is forced into mixing near the bottom, in November (fig. 5; upper chart).

ASSESSMENT OF HEAT IN LAKES

ENERGY BUDGETS AND HEAT BUDGETS

Juday (1940, p. 439) stated "The annual energy budget of a lake may be regarded as comprising the energy received from the sun and sky each year and the expenditures or uses which the lake makes of this annual income of radiation. In general the annual income and outgo substantially balance each other." The income of solar energy is expended in a number of ways, including evaporation, surface losses (reflection, scattering, absorption by snow and ice), conduction, convection, radiation, melting of ice, raising of water and bottom temperatures, and use by organisms.

The heat budget of a body of water is that portion of the energy income which is expended in raising the temperature of the water mass, or a convenient and representative sample of it, from a selected minimum to the summer maximum. As applied by Birge (1915) and later workers, the annual heat budget specifies the number of gram-calories required to warm a column of water of 1 square centimeter base, with height equal to the mean depth of the lake, from the mean winter minimum temperature to the highest mean summer temperature. Such a "budget," expressed in gram-calories per square centimeter of lake surface per year, represents the annual cycle of heat capacity of a lake which can be thermally characterized by single mean temperatures.

Limnological interest in total energy budgets has not been extensive. Except for its application to problems of computing evaporation, a knowledge of all energy values involved in the physical dynamics of a lake is of little more than academic usefulness. Aside from the question of application, the time and instrumentation required to evaluate the various energy expenditures all but limit energy-budget studies to long-term, multiphase investigations such as those which enabled Juday (1940) to describe the energetics of Lake Mendota. Heat budgets, however, are usually concerned only with the heating of the water itself, are relatively simple to determine, and are commonly included in physical descriptions of larger lakes for which sufficient temperature data are available.

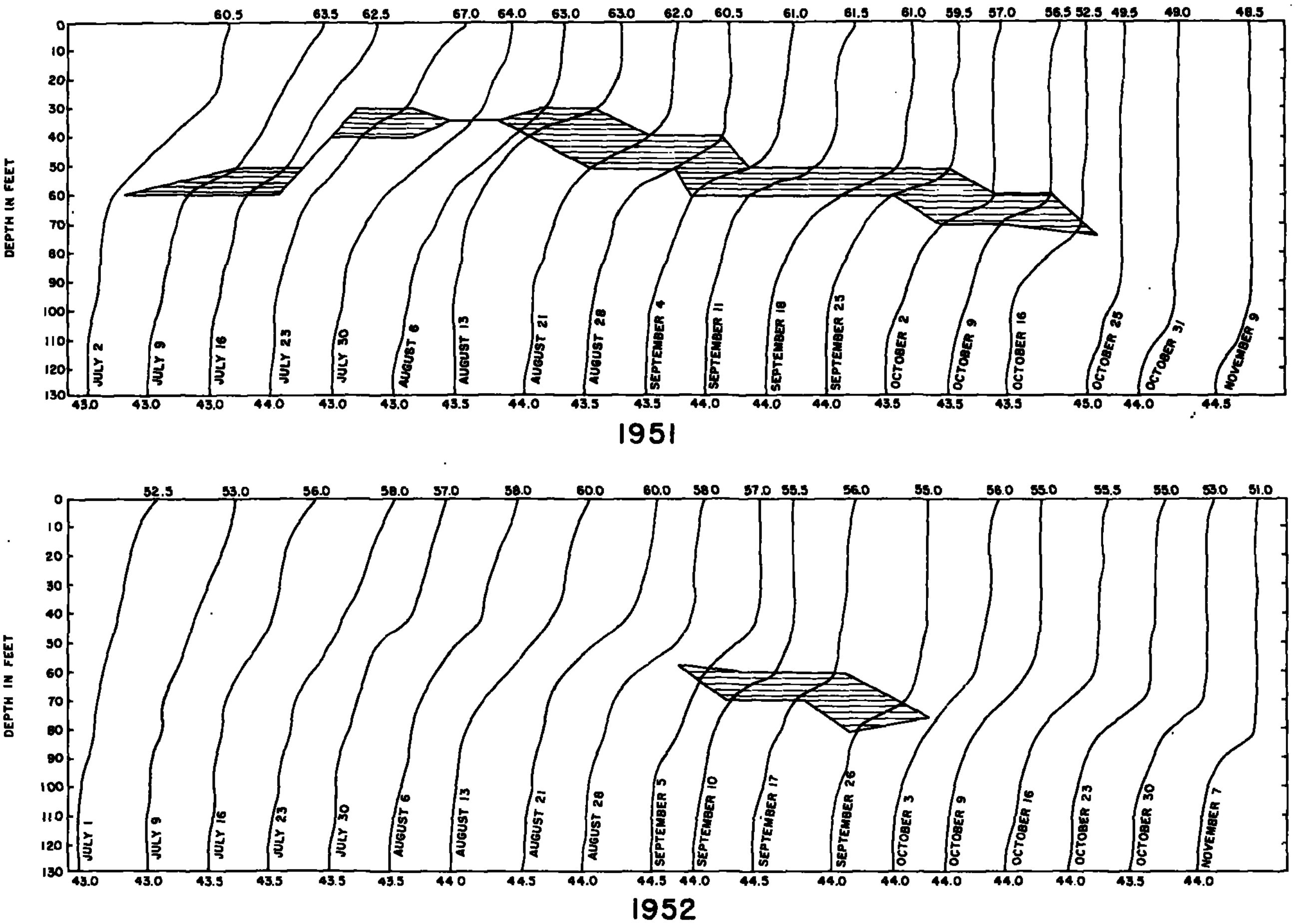


Figure 5.—Summer stratification in Convict Lake, Calif., compared for 2 years, 1951 (upper) and 1952 (lower). The thermocline is indicated by the shaded area. (Temperatures in degrees Fahrenheit.)

HEAT BUDGETS FOR CONVICT LAKE

Annual heat budgets were calculated for Convict Lake according to Birge, with heat expressed in gram-calories per square centimeter of lake surface derived from the product of temperature range and mean depth. To obtain heat budgets for 2 consecutive years (1952 and 1953), a few additional observations were made to determine the mean summer temperature of 1953. The highest mean, which is not reported elsewhere in this paper, was 53.9° F. (12.2° C.) and occurred on August 9.

Annual heat budgets for Convict Lake were 25,210 gram-calories in 1952 and 26,810 gram-calories in 1953. In view of the marked difference in winter and ice cover for the 2 years, and the general similarity of summers except for an excess of cold inflow in 1952, the difference between the two budgets (1,600 calories) represents the approximate range of variation in response to winter conditions. Summer heat incomes above 4° C. were 19,850 gram-calories (79 percent of annual) in 1952 and 21,990 gram-calories (82 percent of annual) in 1953. The average annual heat budget is estimated at between 26,000 and 27,000 gram-calories. Since the budget of 1952 represents an extreme winter, variations outside the range found for 1952 and 1953 would most likely be on the high side and due to exceptional summer weather.

LIMITATIONS OF THE HEAT BUDGET

In outlining dimensional and other limits used in heat-budget comparisons of American and European lakes, Birge (1915) described inland lakes of the "first class" as those which lie under ordinary conditions of topography and altitude, and whose size and depth (at least 10 km. by 2 km. by 30 meters mean depth in eastern United States) permit them to acquire the maximum heat

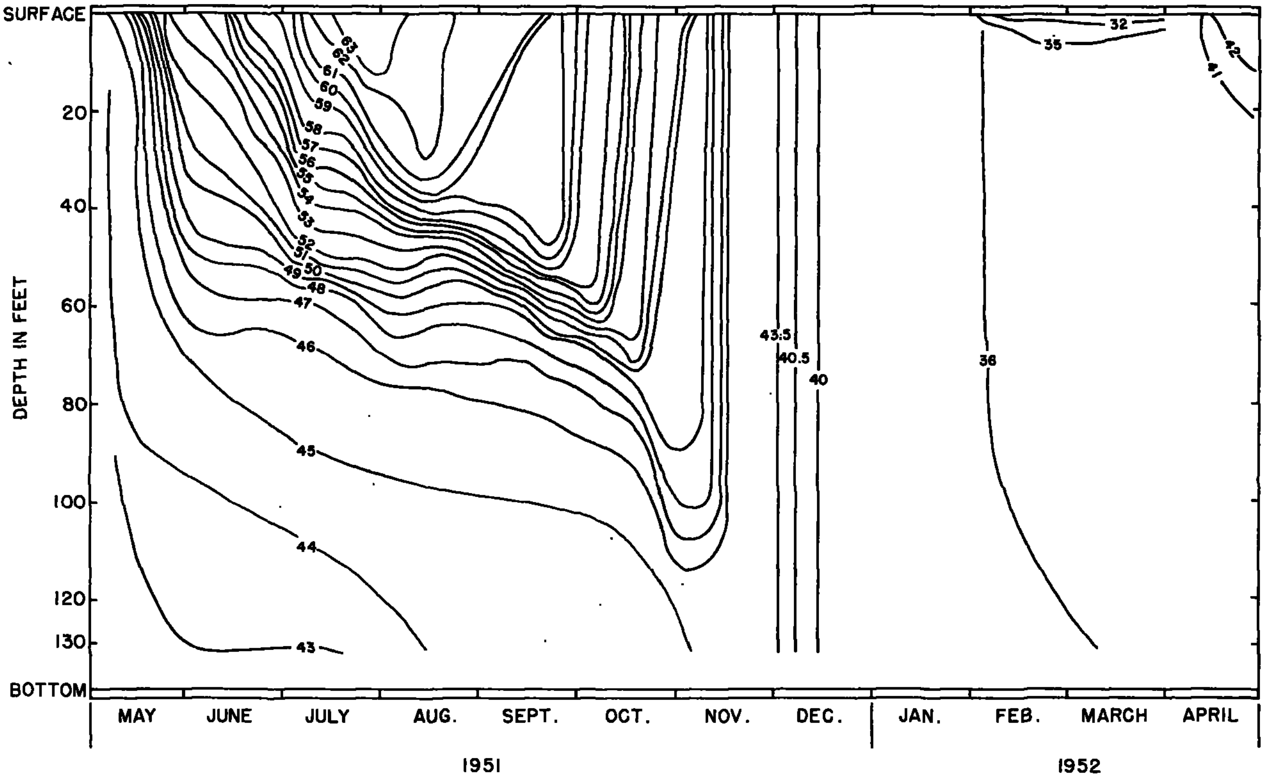


Figure 6.—Seasonal distribution of isotherms in Convict Lake, Calif., May 1951 to April 1952. (Temperatures in degrees Fahrenheit.)

possible under weather conditions of the season. Studies by Rawson (1936) indicated that in a series of Saskatchewan lakes shallower than the 30-meter requirement the heat budgets varied according to mean depth. Similar correspondence between mean depths and crude heat budgets was found among small lakes of the upper Convict Creek Basin (Reimers, Maciolek, and Pister, 1955), and this relationship is probably general among smaller, temperate lakes which are regionally related. It seems certain that a regional selection of lakes would show more variability in mean depth than in temperature range. Small or intermediate lakes, which are limited by area and depth to less than their climatic heat capacities, cannot properly be compared by heat budget with first class lakes, or with each other, except at the expense of explanations concerning relative size, depth, morphometry, or other factors which may bear on the magnitude of the heat budgets. With such added qualifications, heat budgets cannot represent lakes simply, as units, and are not satisfactory for index evaluations of thermal conditions.

Birge further excepted elevated lakes from heat-budget comparisons in the statement that "Lakes whose conditions of climate or location are exceptional, such as those of alpine lakes at considerable elevations, cannot be compared with those in lower and more normal situations." Climatic changes associated with a substantial increase in elevation may be comparable to those resulting from a large increase in latitude. Inflows of cold, snow-fed water have an unusual influence on the heating of many mountain lakes. Variability of these factors further impedes heat-budget comparisons among alpine lakes as a group, since heat budgets are more closely tied with the individual heating capacities of such lakes than with the sensible heat present in them from season to season.

The product of time and temperature is not considered in a heat budget, although this factor should be of great importance in comparative studies of thermal conditions, and particularly in studies of biological heat relations which involve temperature thresholds. In Convict Lake, for

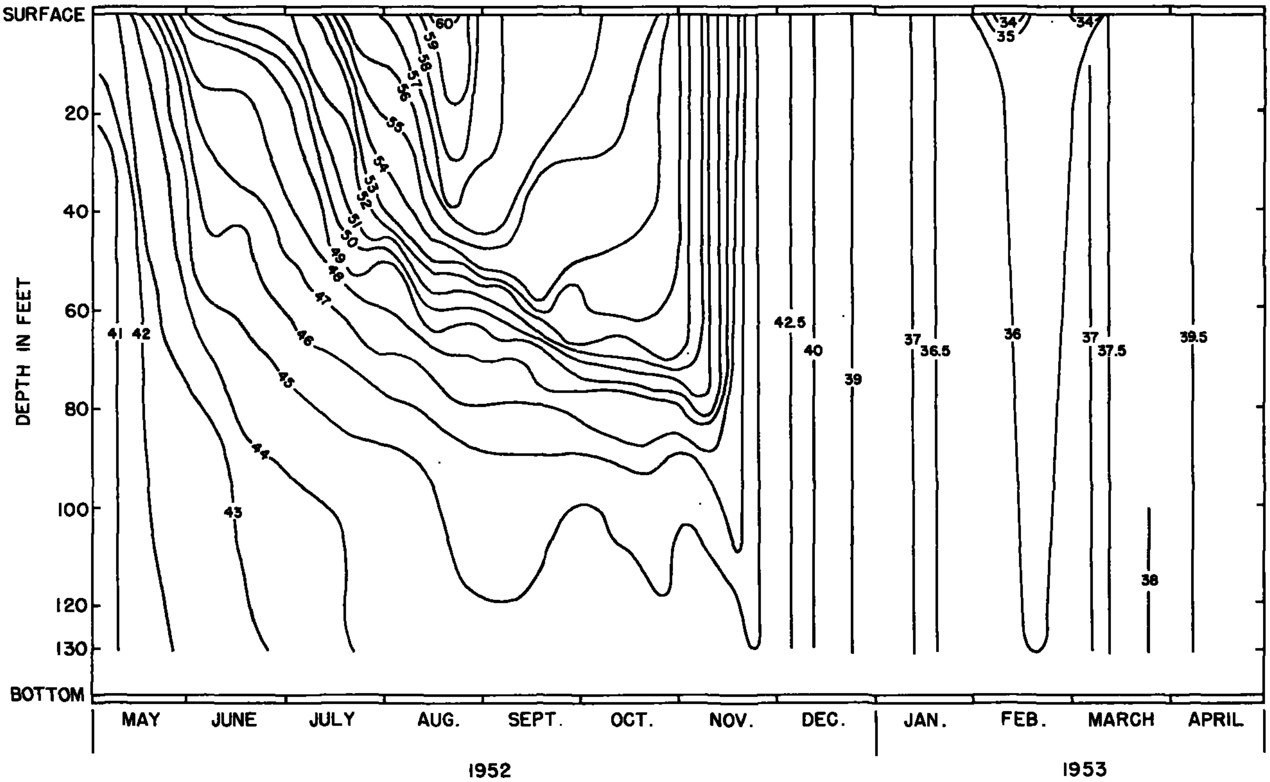


FIGURE 7.—Seasonal distribution of isotherms in Convict Lake, Calif., May 1952 to April 1953. (Temperatures in degrees Fahrenheit.)

example, comparisons of warming progress and the dates of highest mean temperature for two summers (fig. 4) suggest that the main effect of a severe winter is to delay heating in the following summer to the point where the usual mean-temperature peaks may not be reached. The difference in summer heat between the 2 years was due as much to the difference in the length of time that high temperatures were in existence as to the levels of temperature reached. This principle is applicable to comparisons of thermal conditions among lakes as well as among cycles in a single lake. Several lakes of comparable size may have similar heat budgets, yet differ considerably in heat actually in effect over a selected period of time by reason of variations in exposure, altitude, or morphometry, with resulting variations in rates and periods of heating.

Finally, the type of information yielded by the heat budget is not all that is desired in thermal evaluations of lakes or their parts. The actual heat condition of the water, expressed by temperature as the intensity factor, cannot be specified in caloric units. A description of the thermal character of a lake must be based on measurements of temperature, yet the only temperature data required for the calculation of a conventional heat budget are the lowest mean winter temperature (or an arbitrary base such as 0° C., 4° C.) and the highest mean summer temperature. A calculation based on these data, which amount to a gross range of temperature whether for annual or subannual periods, does not provide a cumulative estimate of sensible heat of the water; it only indicates the amount of energy expended to raise the water temperature to the maximum, or from one level to another.

TEMPERATURE SUMMATION AS A BASIS FOR HEAT EVALUATION

The use of temperature summations has a long history in phenology. Most applications have been concerned with the time relation between total accumulated heat above a base temperature and the completion of life-history stages of animals or plants. The base temperature may be the experimentally determined temperature at or below which the process in question cannot be completed successfully, known as the ecological temperature zero, or it may be an arbitrarily selected point which approximates this threshold.

A summation is expressed in units of time × temperature, such as day-degrees or hour-degrees. With such units, "thermal constants" have been described for a wide variety of developmental processes whose rates are regulated by environmental temperatures and whose successful conclusions have been found to depend on reasonably consistent sums of heat within the effective temperature ranges. The theoretical basis of the concept, some applications, and some extensions to include the relation between length of life and metabolic rate as influenced by temperature are reviewed by Allee et al. (1949).

Fish hatcheries have for many years made use of day-degrees as "temperature units" (degrees per day in excess of 32° F.) to predict hatching times of eggs at various water temperatures. The freezing point of water is regarded as the ecological zero for egg development in this application. Development presumably cannot take place at the freezing point, but proceeds at rates which increase with temperatures above freezing.

Although their principal usefulness is in connection with such biological heat relations, temperature summations can also be of service as index measurements of thermal conditions alone in environmental units such as lakes or their biological regions, where the available heat varies throughout seasonal cycles and from lake to lake. A method for thermally comparing lakes and their divisions over selected periods of time is prerequisite to any understanding of possible relations between heat and aquatic productivity in terms of growth or incrementation. Summations provide information that neither caloric estimates nor temperature series alone can provide. They are capable of combining in simple form the two elements—temperature and time—that are essential to an adequate description of thermal character. The resulting thermal units are artificial rather than absolute heat values; however, they are valid as cumulative measurements of heat intensity and are suitable for purposes of comparison.

Since the principle of an experimentally determined "zero" cannot be applied to a lake, the base temperature for summations must necessarily be a constant chosen to represent the lower limit of biological activity in the waters and in the periods to be compared. Within a class such as alpine lakes, the freezing point of water is a logical and convenient base for annual summations. Winter mean temperatures approach the freezing point, and the flora and fauna consist of forms that are adapted to a relatively low range of water temperatures. In subannual comparisons that are to include periods of highest temperatures or other significant parts of the growing season, a higher base temperature may be desirable.

As the mean temperature of a lake represents the entire water body, with temperatures of various strata considered in ratio to their volumes, the summation for a lake as a unit should be made from the selected base temperature to the mean temperature to produce a result that is independent of volume and suitable for comparison with totals from other lakes. Similarly, summations should be made to the mean temperatures of the divisions or biological regions that are of interest in subtotal comparisons. Accurate knowledge of mean temperatures requires reasonably thorough hydrographic surveys, but such preliminary work is necessary for the calculation of acceptable morphometric values in any event.

One factor that limits summations to scheduled investigations is the need for a series of several mean temperatures distributed uniformly over the year. There is no escaping the fact that an annual accumulation of thermal units, sufficiently accurate to be used for comparing lakes, requires a number of observations on each lake that is adequate to represent the time and temperature cycle involved. Because seasonal changes in the mean temperatures of most lakes are notably slow and regular, the number of observations for the year may often be reduced to a feasible minimum. For example, reduction of the Convict Lake annual data to monthly intervals gave the same accuracy as weekly observations.

SUMMATION PROCEDURE

Trials of the summation method were conducted with 32° F. as a base point, and the day-degree values are accordingly referred to as temperature units.

With a series of mean lake temperatures at hand, the assembly of data is simple, since the only variables are the mean temperatures and numbers of days between temperature observations. The procedure used with the Convict Lake data is as follows:

1. Average the mean temperatures for each consecutive pair of observation dates to obtain the best estimate of the mean temperature for the interval.
2. Subtract 32 from the interval mean temperature to obtain temperature units per day.
3. Multiply temperature units per day by the number of days in the interval between observations.
4. Add the products for intervals through the desired period to obtain total temperature units.

Formulated,

total temperature units=

$$(T_m^{i(1)}-32)\,(TI_1)+(T_m^{i(2)}-32)\,(TI_2)+\ldots\ldots\,(T_m^{i(n)}-32)\,(TI_n),$$

in which T_m^i is the mean temperature for an interval between pairs of observation dates, TI is the length of a time interval in days, and n is selected to limit the summation to the desired period.

ANNUAL SUMS FOR CONVICT LAKE

Tables 5 and 6 present the summations of mean temperature for Convict Lake for the 2 years (May 1951 to May 1953) according to the procedure presented in the previous section. The results of both weekly and monthly intervals are tabulated to show separate totals for the year. The near identity of the weekly and monthly figures for each year is considered sufficient evidence of the adequacy of monthly observations in an annual cycle for any lake whose rates of heating and cooling are not radically greater than those observed for Convict Lake. As decimal selection in the computation of interval mean temperatures could cause bias in the product when temperature units are multiplied by days, particularly when the interval is large, these means and their temperature units (cols. 4 to 7) were carried to an extra decimal place where necessary to avoid such bias. The annual sums are therefore free of the influence of decimal selection at the weekly or monthly level, and the effect of such selection in

TABLE 5.—*Summations of mean temperatures above 32° F. in Convict Lake, by weekly and monthly intervals, May 1951 to May 1952*

Period	Time interval (TI) in days		Mean temperature of interval		Mean daily temperature units (TU)		Temperature units in time interval (TU × TI)	
	Weekly	Monthly	Weekly	Monthly[1]	Weekly	Monthly	Weekly	Monthly
May 7-14	7	35	43.65	45.60	11.65	13.60	81.6	476.0
May 14-21	7		44.90		12.90		90.3	
May 21-28	7		48.85		14.85		104	
May 28-June 4	7		48.00		16.00		112	
June 4-11	7		48.00		16.00		112	
June 11-18	7	28	48.35	49.80	16.35	17.80	114.4	498.4
June 18-25	7		48.80		16.80		117.6	
June 25-July 2	7		49.90		17.90		125.3	
July 2-9	7		51.25		19.25		134.8	
July 9-16	7	35	51.35	52.60	19.35	20.60	135.4	721.0
July 16-23	7		51.90		19.90		139.3	
July 23-30	7		52.80		20.80		145.6	
July 30-Aug. 6	7		53.00		21.00		147	
Aug. 6-13	7		53.35		21.35		149.4	
Aug. 13-21	8	29	53.50	53.15	21.50	21.15	172	613.4
Aug. 21-28	7		53.15		21.15		148	
Aug. 28-Sept. 4	7		52.80		20.80		145.6	
Sept. 4-11	7		52.70		20.70		144.9	
Sept. 11-18	7	28	53.15	52.45	21.15	20.45	148	572.6
Sept. 18-25	7		53.25		21.25		148.8	
Sept. 25-Oct. 2	7		52.60		20.60		144.2	
Oct. 2-9	7		52.25		20.25		141.8	
Oct. 9-16	7	31	51.10	50.10	19.10	18.10	133.7	561.1
Oct. 16-25	9		49.30		17.30		155.7	
Oct. 25-31	6		48.30		16.30		97.8	
Oct. 31-Nov. 9	9		48.00		16.00		144.0	
Nov. 9-16	7	28	46.75	44.25	14.75	12.25	103.2	343.0
Nov. 16-23	7		44.80		12.80		89.6	
Nov. 23-30	7		43.80		11.80		82.6	
Nov. 30-Dec. 7	7		42.00		10.00		70.0	
Dec. 7-14	7	61	40.30	38.15	8.30	6.15	58.1	375.2
Dec. 14-Feb. 6	54		37.95		5.95		321.3	
Feb. 6-14	8	33	35.80	35.70	3.80	3.70	30.4	122.1
Feb. 14-21	7		35.70		3.70		25.9	
Feb. 21-Mar. 11	18		35.60		3.60		64.8	
Mar. 11-25	14	21	35.60	35.60	3.60	3.60	50.4	75.6
Mar. 25-Apr. 1	7		35.60		3.60		25.2	
Apr. 1-May 9	38	38	38.40	38.40	6.40	6.40	243.2	243.2
Total	367						4,597.9	4,601.6

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[1] Monthly interval mean temperatures are averages of initial and final monthly temperatures.

the product itself (last column) is negligible. Because of irregular intervals at certain times, the terms "weekly" and "monthly" are used somewhat loosely in the tabulations. The agreement of yearly totals on both interval bases, however, is again ample evidence that the slow seasonal change in mean temperature is capable of absorbing irregularities in intervals as well as reasonably large intervals. Intervals longer than a month do not appear to be adequate to follow the annual mean temperature curve. Results of trials with 9 and 7 observations a year (intervals of approximately 1½ and 2 months) were not consistent with those of monthly and weekly observations.

THERMAL COMPARISONS WITH TEMPERATURE UNITS

The difference in temperature units between the Convict Lake heat cycles of 1951 and of 1952 may be used to demonstrate the applicability of the summation method to annual or cyclic comparisons; but for this purpose it is necessary to adjust the time periods in tables 5 and 6. It has been shown that the severe winter of 1951–52 resulted in delayed heating as well as generally lower water temperatures in the following spring and summer, so that the 1952 cycle from winter minimum to winter minimum involved considerably less heat than the preceding cycle. However, the annual temperature unit totals in tables 5 and 6 were computed on a May-to-May basis to include all data for 2 noncalendar years. The below-normal temperatures of early 1952 (prior to May) are therefore actually appended to the 1951 cycle (table 5), and the relatively high, early spring temperatures prior to May 1953 are added to the 1952 cycle (table 6). This overlapping of cycles has a compensating effect on both "data

TABLE 6.—*Summations of mean temperatures above 32 ° F. in Convict Lake, by weekly and monthly intervals, May 1952 to May 1953*

Period	Time interval (TI) in days		Mean temperature of interval		Mean daily temperature units (TU)		Temperature units in time interval (TU × TI)	
	Weekly	Monthly	Weekly	Monthly[1]	Weekly	Monthly	Weekly	Monthly
May 9–16	7	28	41.90	43.45	9.90	11.45	69.3	320.6
May 16–23	7		43.05		11.05		77.4	
May 23–29	6		44.15		12.15		72.9	
May 29–June 6	8		45.25		13.25		106.0	
June 6–16	10	33	45.60	46.70	13.60	14.70	136.0	485.1
June 16–24	8		45.75		13.75		110.0	
June 24–July 1	7		46.45		14.45		101.2	
July 1–9	8		47.30		15.30		122.4	
July 9–16	7	35	48.15	49.70	16.15	17.70	113.0	619.5
July 16–23	7		49.40		17.40		121.8	
July 23–30	7		50.10		18.10		126.7	
July 30–Aug. 6	7		50.35		18.35		128.4	
Aug. 6–13	7		51.20		19.20		134.4	
Aug. 13–21	8	28	52.10	51.70	20.10	19.70	160.8	551.6
Aug. 21–28	7		52.05		20.05		140.4	
Aug. 28–Sept. 5	8		51.70		19.70		157.6	
Sept. 5–10	5		51.75		19.75		98.8	
Sept. 10–17	7	29	51.65	51.60	19.65	19.60	137.6	568.4
Sept. 17–26	9		51.50		19.50		175.5	
Sept. 26–Oct. 3	7		51.55		19.55		136.8	
Oct. 3–9	6		51.60		19.60		117.6	
Oct. 9–16	7	29	51.50	50.65	19.50	18.65	136.5	540.8
Oct. 16–23	7		51.45		19.45		136.2	
Oct. 23–30	7		50.80		18.80		131.6	
Oct. 30–Nov. 7	8		50.00		18.00		144.0	
Nov. 7–18	11	34	47.95	44.95	15.95	12.95	175.4	440.3
Nov. 18–24	6		45.45		13.45		80.7	
Nov. 24–Dec. 4	10		43.70		11.70		117.0	
Dec. 4–11	7		41.35		9.35		65.4	
Dec. 11–17	6	32	40.10	38.55	8.10	6.55	48.6	209.6
Dec. 17–23	6		39.55		7.55		45.3	
Dec. 23–Jan. 12	20		38.00		6.00		120.0	
Jan. 12–19	7	30	36.75	36.55	4.75	4.55	33.2	136.5
Jan. 19–30	11		36.45		4.45		49.0	
Jan. 30–Feb. 11	12		36.25		4.25		51.0	
Feb. 11–19	8	28	36.05	36.85	4.05	4.85	32.4	135.8
Feb. 19–Mar. 6	15		36.35		4.35		65.2	
Mar. 6–11	5		37.15		5.15		25.8	
Mar. 11–31	20	28	38.55	38.60	6.55	6.60	131.0	184.8
Mar. 31–Apr. 8	8		39.55		7.55		60.4	
Apr. 8–15	7	32	39.85	41.00	7.85	9.00	55.0	288.0
Apr. 15–22	7		40.50		8.50		59.5	
Apr. 22–May 2	10		41.25		9.25		92.5	
May 2–10	8		42.00		10.00		80.0	
Total	366						4,480.3	4,481.0

[1] Monthly interval mean temperatures are averages of initial and final monthly temperatures.

years" as tabulated, and the indicated temperature unit totals are not representative of the cycles.

To compare the cycles of the 2 years with present data, it is therefore necessary to eliminate the early spring temperatures, and to include in the summations only the temperature units between the initial May dates and winter dates chosen to represent near-minimum temperatures. Suitable periods from tables 5 and 6 are May 7 to December 14, 1951, and May 9 to December 16, 1952. Although temperatures had not reached the minimum at mid-December, these winter dates approximate the time when an ice cover forms on the lake, they permit equal comparison periods for the 2 years, and, on a weekly-interval basis, their mean temperatures are nearly identical for both years. Temperature-unit totals for the two periods (from tables 5 and 6) were 3,843.6 for 1951 and 3,566.8 for 1952. The difference of 277 units is significant. In a little over 7 months in 1951 there were roughly 6,650 more hour-degrees of heat above the freezing point than in a similar period in 1952. Moreover, a further comparison of two 4-month periods (May 7 to Sept. 11, 1951, and May 9 to Sept. 13, 1952) gives an almost equal difference of 273 temperature units, indicating quantitatively that the greatest difference in available heat between the two cycles was effective during late spring and summer months when higher temperatures prevailed.

In the same manner, annual, subannual, or shorter periods of interest may be compared among lakes in a given year. Data for 25-day periods in July and August 1953 are available for a short-term comparison among 10 lakes of the Convict Creek Basin, ranging in elevation from 7,583 feet (Convict Lake) to 10,950 feet (Lake Constance). In table 7, the lakes are arranged according to interval mean temperatures and summations above freezing for the 25-day intervals, which were as nearly simultaneous as travel conditions and other work permitted. These periods are too early to include highest summer mean temperatures, yet they are far enough advanced that the temperature differences among lakes would be changed but slightly by the amount of further heating to be expected during August.

It may be seen that there is sufficient variability of summations in such periods of representative summer temperatures to scale these related lakes for thermal comparison, or to correlate temperature sums with biological variables in a definite unit of time.

Also given for each lake (table 7) are mean depth, range of mean temperatures in the period, and number of gram-calories required to warm the standard "heat budget" unit of water (mean depth × 1 sq. cm.) from the freezing point to the interval mean temperature. The latter value may be represented as the energy content, above the freezing point, of a mean column of water at the interval mean temperature. This series of energy values, as influenced by the mean depths of the lakes, is in no way comparable with the series of summations of existing temperatures. The inclusion of mean depths essentially characterizes the lakes volumetrically and makes them noncomparable.

If the tabulated caloric values were factored by the mean depths, the result would be energy content per mean cubic centimeter, expressed in gram-calories as the number of degrees (centigrade) of the interval mean temperatures. Such values would be comparable by ratio to the temperature

TABLE 7.—*Thermal characteristics of 10 lakes in Convict Creek Basin, by 25-day periods, July and August 1953*

[Temperature in degrees Fahrenheit except in calculation of gram-calories]

Lake	Mean temperatures					Temperature units ((T^i_m-32) 25)	Gram-calories (T^i_m-0° C.)	Mean depth (feet)
	Initial		Final		Interval (T^i_m)			
	°F.	Date	°F.	Date				
Convict	51.8	7/15	53.9	8/9	52.9	522	31,007	88
Bighorn	45.7	7/13	51.5	8/7	48.6	415	4,471	16
Cloverleaf	43.9	7/15	52.5	8/9	48.2	405	3,276	12
Bright Dot	43.2	7/13	51.0	8/7	47.1	378	9,946	39
Genevieve	44.3	7/14	48.5	8/8	46.4	360	14,824	61
Mildred	44.0	7/13	48.1	8/7	46.1	352	6,478	27
Edith	42.6	7/14	46.3	8/8	44.5	312	12,544	59
Witsanapah	41.2	7/13	46.6	8/7	43.9	298	5,610	28
Dorothy	42.0	7/16	43.8	8/10	42.9	262	25,193	136
Constance	40.0	7/18	44.1	8/12	42.1	252	12,074	71

summation values, but they would have no connection with the 25-day period; they could apply to unequal periods, or to any given instant at the proper mean temperatures. If caloric evaluations were limited to the temperatures of the 25 days, based on initial and final mean temperatures and excluding mean depths, the results would be expressions not of energy content but of changes in energy storage. A period so situated as to indicate no change in mean temperature would then have no calories indicated.

In such comparisons of lakes, the central interest is in the heat of the water, with regard to time but without regard to volume. For this, temperature summations give adequate evaluations of heat. Caloric assessments are not suitable because gram-calories are intimately concerned with a unit volume of water (1 gram=1 cc.) and are expressible over a period of time only as rates of gain or loss.

TEMPERATURE AND PERIPHYTON PRODUCTIVITY IN CONVICT LAKE

In 1953 and 1954, continuous sampling of periphyton was attempted in Convict Lake as part of a current investigation to determine the suitability of this material as an indicator of basic productivity, primarily in oligotrophic alpine lakes. Techniques of periphyton sampling and analysis and results of preliminary 1952 sampling in the Convict Creek Basin lakes were reported by Nielson (1953). Briefly, the method consists of collecting and analyzing 25-day increments of attachment material on known areas of artificial substrate suspended in various depth strata. In deeper lakes, stations are located at appropriate depths to sample littoral, limnetic, and profundal zones. After controlled air drying, weighing, ignition, and reweighing, the material is represented as total dry residue, organic fraction, and ash fraction in milligrams per square decimeter of substrate corrected to mean values for the entire lake or for the division that is of interest.

In Convict Lake sampling, the relation between environmental temperature and periphyton production per time unit was of interest as a reference to the usefulness of periphyton for index purposes. Initial and final temperature series were recorded for each 25-day sampling period, and summations based on interval mean temperatures were used to determine a relationship. Except for a January to April gap when the periphyton sets were inaccessible, the five sampling periods in which sets remained undisturbed were consecutive and represent the transition from winter to summer temperatures. Temperature summation data and organic periphyton values for these periods are presented in table 8, and have been plotted on figure 8 with a regression line fitted by the method of least squares. The coefficient of correlation for the relationship (+0.966) was highly favorable, and from this it may be concluded that the periphyton assemblage is measurably sensitive to variations of temperature within the observed range.

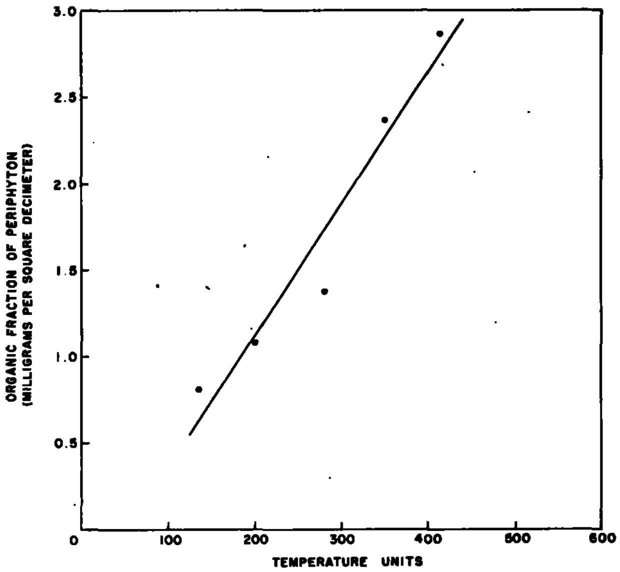

FIGURE 8.—Relation of organic periphyton increment to temperature sums above 32° F. for five 25-day periods in Convict Lake, Calif., November 1953 to July 1954. Line shown is least squares fit: $r=+0.966$; $y=-0.40+0.0076x$.

TABLE 8.—*Mean temperatures, temperature units, and mean periphyton quantities for five 25-day periods in Convict Lake, 1953 and 1954*

Sampling period	Mean temperatures			Temperature units	Organic periphyton [1]
	Initial	Final	Interval		
1953					
Nov. 17–Dec. 12	42	38	40	200	1.09
1954					
Dec. 12–Jan. 6	38	37	37.5	137.5	0.81
Apr. 22–May 17	41	45.5	43.2	280	1.38
May 17–June 11	45.5	46.6	46	350	2.36
June 11–July 6	46.6	50.7	48.6	415	2.87

[1] Lake mean values, expressed in milligrams per square decimeter of sample surface.

Of principal interest here, however, is the usefulness of temperature summations in determining such a relationship. Since the amount of attached material at the end of a 25-day period constitutes the sum of daily increments of attachment and daily increments of growth (of the material already attached), and since these two components are very difficult to separate (Newcombe 1950), it is desirable for the purpose of correlation to represent each periphyton sample as the total amount which has accumulated in a sampling period rather than as an indication of the rate of incrementation. In this connection, it is more accurate to represent the corresponding temperature structure as a sum than as the existing temperature condition. Temperatures alone do not characterize the periods quantitatively, whereas summations permit a direct quantitative association of temperature with the periphyton measurement on a time basis.

VALUE OF TEMPERATURE SUMMATION

In the continuing search for reliable indices of lake productivity, information indicative of the extent to which production is controlled by temperature may be of considerable importance, particularly in alpine situations. Rawson (1939) pointed out that in extreme oligotrophy low temperature is a major if not the limiting factor in production, and cited Lundbeck (1934) as a proponent of thermal oligotrophy in some lakes of the Alps. McCombie (1953) presented evidence of the controlling influence of temperature on phytoplankton growth and abundance. Rawson (1942) found a relation between the average standing crops of plankton and the mean temperatures of upper strata in a series of alpine lakes of western Canada, but he concluded (1953) that the standing crop of plankton is unlikely to provide a satisfactory index of basic productivity for lakes because of difficulties of sampling, rapid turnover and radical short-term changes in abundance of the crop, and small effective range of variation among lakes. Limitations of standing-crop measurements have been noted by others, and it is well recognized that an ideal measure of biological productivity should include the time factor and be expressible as a rate of production. Clearly, the temperature relations of any such index measurement should be known, for, to be valid, the index must conform with the known influences (heat, light, and nutrients) that act in combination to control or limit productivity in the larger sense.

It is suggested that the summation of temperatures constitutes a useful tool for the evaluation of heat intensity in lakes, both for problems of thermal comparison and for the investigation of biological temperature relations in which time is a factor. Advantages of the method for either purpose are (1) independence of depth, volume, and heat capacity factors which restrict the utility of caloric evaluations; (2) inclusion of the time factor, which in effect adds an extra dimension to temperature data; (3) applicability to selected comparison periods in accordance with objectives, seasonal limitations on field work, et cetera; and (4) adaptability to comparisons among selected parts of lakes (e. g., epilimnia of thermally complex lakes) as well as among entire lakes. In the study of temperature relations, the inclusion of time by the simple expedient of summing mean temperatures is perhaps less accurate than some situations require. Still, the biological assessments of lake productivity in general are far from a state of exactitude and a summation method would appear to be helpful in a further understanding of the role of temperature.

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