THERMAL CONVECTION IN LAKE WASHINGTON, WINTER 1962-1963

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WINTER 1962-1963

by

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ABSTRACT

The winter convection regime in Lake Washington was investigated, especially the flow along the bottom off the mouths of some of the many shallow bays. The density of fresh water at a given depth, or pressure, is a function of its temperature, so temperature was measured in detail in a portion of the lake during the winter cooling period of 1962-63. The isotherms at the edges of the lake were found to be closely packed and roughly parallel to the sloping bottom. This structure frequently extended to the middle and occasionally across the lake whereas most of the water column in the center of the lake was nearly isothermal. Volume transport was computed from consideration of the amount of heat removed from the deep water of the lake. From the volume transport off Juanita Bay the velocity of the water down the side of the lake was estimated to be 2 cm/sec.

INTRODUCTION

PURPOSE

The purpose of this study is to describe convection in Lake Washington associated with winter cooling under conditions of low wind and large cooling rates. It was necessary to (1) define the vertical and horizontal temperature structure of the lake, (2) compute the heat budget of the lake during the period of winter cooling, (3) compute the vertical transport and associated velocities required for bottom water replacement by convection currents.

NATURE OF THE PROBLEM

The density structure of Lake Washington gives a measure of the potential for flow of the system. Since the density of fresh water at a given depth is a function of temperature and the amount of dissolved or suspended material, measurement of these variables at successive times will give the potential for flow of the system. In addition, it will be possible to define the advective flow in the layers of the lake below the depth of direct surface influence, as all changes of heat at depth are the result of advection (diffusion is considered to be relatively unimportant because the water is nearly isothermal).

PREVIOUS WORK

The term "overturn" was introduced by Whipple in 1895 (Birge, 1904) to describe the annual replacement of bottom water in lakes associated with winter cooling. This choice of terminology appears to be unfortunate because it implies that individual water columns become unstable and capsize. Early workers, particularly those working in

shallow lakes in areas where winter cooling is so great that the lakes freeze, tended to discount the importance of convection. Birge (1910) went so far as to say,

> "convection currents are far less important agents for distributing heat than are mechanical currents caused by the wind. Indeed, it would be difficult to show that convection currents have any such efficiency in carrying heat as to make them worth serious consideration."

More recently, Mortimer (1955) recognized a problem with the term "overturn" and was careful to state, "'overturn' connotes the fact that bottom layers previously isolated below the thermocline are brought to the surface." Mortimer goes on to say that such an indefinite statement is necessary because so little attention has been given to water movements leading to the destruction of the thermocline.

The limnology of Lake Washington was discussed by Scheffer and Robinson (1939). They found that bottom water replacement takes place over an extended period in the winter, from December to February or March. The temperature in Lake Washington does not go below the temperature of maximum density of fresh water, 4° C, so that there is no winter stable period.

Rattray, Seckel and Barnes (1954) studied the salt balance in the Lake Washington Ship Canal. They repeatedly occupied a station in the deep part of the lake off Madison Park. They found that there was bottom water replacement even in the presence of a density gradient. They showed that with a density increase of 1.3×10^{-4} g/cm^3 from top to bottom, it was still possible to have an "overturn". The energy for the mixing presumably came from the wind. They also considered the effect of river inflow and concluded that 25 percent of the lake volume was flushed each year.

Gould and Budinger (1958) proposed that convection currents were responsible for the W-shaped bottom profile of Lake Washington. They postulated that currents arising in the shallow bays around the edges of the lake were strong enough to erode the foot of the slopes, or at least to prevent deposition of sediments there. This is an alternative mechanism for the replacement of bottom water in the presence of a density gradient. The water need only become very dense locally in the shallow bays; it can then flow under the water in the central portion of the lake, displacing the local water, with its associated density structure, upward into regions where the structure can be altered by wind action and heat exchange across the surface. This process will continue as long as water in the bays is colder than the main body of the lake, which agrees with the observation of Scheffer and Robinson that bottom water replacement occurs over an extended period.

Church (1942) worked on the annual temperature cycle in Lake Michigan. He found that with a density increase of 1.5×10^{-4} g/cm^3, over the depth range encountered in Lake Washington, stability was maintained against a wind of Beaufort force 2. In Lake Michigan, however, the wind might have been the dominant factor in the breakdown of the thermocline. Winter winds in that area were very strong and there were few shallow bays to serve as source areas of cold bottom water.

DESCRIPTION OF LAKE WASHINGTON

Lake Washington is a narrow lake with its long axis in a north-south direction. It is about 1.5 miles wide and 18.5 miles long. Along

much of the length of the lake there is a rise of 2 to 10 m, giving transverse profiles a subdued W-shape (fig. 1). The margin of the lake is indented by many shallow bays. The lake communicates with the salt water in Puget Sound by an 18-mile canal with a lock at the seaward end. A more extensive discussion of the morphology of the lake is given in Gould and Budinger (1958).

MATERIALS AND METHODS

Temperature was measured with a thermistor which formed one leg of a Wheatstone bridge. The bridge output, which was nearly linear with temperature, was fed into a millivolt recorder. The correction to the thermistor output for heating by the bridge current was always less than 0.01° C; the correction was considered negligible.

In normal operation, the full scale recorder range was 2° C, giving a sensitivity of 0.01° C. The system was calibrated by the Applied Physics Laboratory, University of Washington. The accuracy of the system was checked by field comparisons with reversing thermometers. A bias of 0.13° C was found. All temperature determinations have been corrected for this bias which did not change during the program.

The standard deviation of the difference between temperatures determined by the reversing thermometers and the thermistor was 0.031° C. Part of the variability is associated with the limits of accuracy of the reversing thermometer and part with the inaccuracy of the thermistor. The standard deviation of the averaged determinations by a pair of reversing thermometers has been given as 0.012° C (Fofonoff, 1963). Since the variance of a sum of independent random variables equals the

sum of the variances, the standard deviation of the thermistor approximates 0.028° C. The precision of the thermistor (as defined by twice the standard deviation) is therefore about 0.05° C, which is about one-half the precision of the reversing thermometers.

Chlorinity was determined by the Volhard method. The carbonates and sulfides in the lake water interfere with the Mohr titration which is usually used on sea water.

Positions were determined either by horizontal sextant angles or by magnetic bearings from a pelorus on the flying bridge.

INVESTIGATION

THE TEMPERATURE STRUCTURE

The vertical temperature structure at a station on the east side of Lake Washington off Fairweather Point was monitored during the winter of 1962-63 (fig. 2). Cooling continued from the first observation on 26 December until 31 January. During this time, no unstable water columns were observed, with the possible exception of the last few meters on 29 and 30 January. A temperature increase in the bottom layers existed in previous years (Rattray, Seckel and Barnes, 1954) when dissolved salt stabilized the water column.

If the water columns observed on 29 and 30 January were stabilized by dissolved salt, there would have to be a chlorinity difference of 0.007 per mille in the bottom 3 m. The temperature inversion was too close to the bottom to permit sampling there. The inversion also could have been caused by a turbidity current moving out into the deep water. The column would remain stable as the sediment settled and the inversion disappeared. Measurements with a hydrophotometer in shallow water indicated that there was suspended material near the bottom.

The lake off Fairweather Point was isothermal on 26 December and 10 January. On 14 January the surface layer had cooled. but there was a large temperature decrease in the last 7 to 8 m. The decrease was present on 21 January, while the thermocline was much shallower than it was earlier. Surface warming began on 1 February, but deep water continued to cool. Cooling was probably caused by the arrival of cold water which was in transit when surface warming began. By 6 March,

warming had taken place at all levels and thermal stratification began.

Stratification was more pronounced by 24 April and the temperature had increased throughout the water column, suggesting an appreciable movement of water from the surface to depth during the initial warming. The process of replacement of bottom water during warming is different from replacement during cooling. The source of energy for replacement during warming is the wind. The spring storms cause some mixing to the bottom. In 1963, winds stronger than any during cooling period occurred on 3 and 26 February, 15, 18, 28, 29, 30 March, 15 and 22 April (table I).

Thirteen sections were made from Sand Point to Juanita Bay (fig. 3 to 9). They covered the two major cold periods in January, and the return of stratification with warming. In all sections during the cooling period, there was a large tilt to the isotherms near Juanita Bay. The tilted isotherms and the low temperatures in the bay was an indication of flow out of the bay along the bottom.

The cold water often found in the deep on the Sand Point side of the section did not appear to have originated in Juanita Bay, as the isotherms were not continuous from the mouth of the bay. That water was too cold to have come from Juanita Bay. Water from that source would have been warmer because of mixing currents. The surface water near Sand Point was never as cold as the water in the deep paths of the section. The coldest water was in the thalweg, the line of greatest depth along the axis of the lake. The most probable origin of that water was in the northern portion of the lake.

A section from Kenmore to Fairweather Point was prepared to trace the origin of the cold water in the thalweg (fig. 10). The section is a

composite of sections from Kenmore to Sand Point on 27 January and from Sand Point to Fairweather Point on 25 January. The temperatures in the portion of the earlier section were adjusted to the levels prevailing 27 January.

There was a marked similarity between the temperature structures in the north end of the lake and the Sand Point-Juanita Bay sections. This was expected because the north end of the lake has extensive shallow areas for the formation of very dense water. The cold water at the foot of the slope in the Kenmore region presumably was not isolated from the cold water in shallower depths, as continuity was maintained along the thalweg.

A section from Sand Point to the deepest part of the lake, off Leschi Park, was taken on 21 January (fig. 11). The cold water in the central region corresponded in position to both Fairweather Bay on the east and to Union Bay on the west and probably represents the cold water flowing into the deepest part of the lake from each side.

HEAT BUDGET

Knowledge of the heat budget made it possible to compare the observed heat loss in a portion of the lake with the computed heat loss expected from meteorological conditions. If the observed heat loss and the computed heat loss agreed, then all of the heat was removed through the surface. If the observed and computed heat loss disagreed, then there must have been exchange of water and heat across the lateral boundaries of that part of the lake.

The terms in the heat budget equation were incoming radiation (Q_s), reflected radiation (Q_r), back radiation (Q_b), evaporation (Q_e), and conduction of sensible heat (Q_h). The incoming radiation was measured with an Eppley pyrheliometer on top of a three-story building (Johnson Hall on the University of Washington campus) about 1.5 miles from the lake. The remaining terms were calculated from expressions given by T. Laevastu (1960), modified slightly for fresh water.

$$Q_r = 0.15\ Q_s - (0.01\ Q_s)^2$$

$$Q_e = (0.26 + 0.077\ V)\ (e_w - e_a)\ (0.1\ L)$$

$$Q_b = 20.65\ (14.38 - 0.09\ T_w - 0.046\ r)\ (1 - 0.0765\ C)$$

$$Q_h = 36\ (0.26 + 0.077\ V)\ (T_w - T_a)$$

Where all of the Q's are in g cal/cm^2/day:

T_w is the temperature of the water surface in °C,

T_a is the temperature of the air in °C,

r is the relative humidity in percent,

C is the cloud cover in tenths,

V is the wind speed in m/sec,

e_w is the saturated vapor pressure at the temperature of the surface in mb,

e_a is the vapor pressure of the air above the water surface in mb,

L is the latent heat of vaporization in cal/gm.

Laevastu uses 39, instead of 36, as the coefficient in his equation for the transfer of sensible heat. The value comes from the choice of the constant in the Bowen ratio. Limnologists have used a slightly different value of this constant, resulting in a smaller coefficient in the equation of sensible heat transfer (Anderson, 1954).

The meteorological data used to make the heat budget calculations were obtained from the weather facility at Sand Point Naval Air Station (table II). The anemometer was 10 m above the lake level, the wet and dry bulb thermometers were 8 m above lake level. The two major cooling periods in January 1963, with daily average temperatures less than 0° C, had an associated increase in wind speed (fig. 12). The heat budget was computed from 10 January to 1 February (table III).

DOWNSLOPE CURRENT OFF JUANITA BAY

There are two main assumptions in the calculation of downslope current off Juanita Bay. The first is that there is no flow into or out of the Sand Point-Juanita Bay section, so that all of the heat loss must take place at the surface. The second is that the influence of surface processes does not extend below 20 m. If this assumption is violated, the computed current will be too high. For the purposes of this calculation, the Sand Point to Juanita Bay section was divided into three parts.

The volume transport was determined by the amount of water at the average temperature of Juanita Bay, region II, which would have to mix with the water in region I to produce the observed heat loss there. The formula used was:

$$V = \frac{\Delta \text{Heat}}{(T_I - T_{II}) \rho \, C_p \Delta t}$$

where V is the volume transport in cm^3/sec;

Δ Heat is the change in heat of the water in region I from one time to the next,

T_I is the average temperature of region I,

T_{II} is the average temperature of region II,

ρ and C_p are density and specific heat (assumed to be 1),

Δt is the time in seconds between sections.

The current velocity was found by dividing the volume transport by the area through which the current flowed. The vertical temperature structure in the slope region off Juanita Bay showed that the flow varied in thickness from 1 to 5 m. Since the thickness of the flow was usually closer to 5 m, that value was used in the calculation. This choice gave a conservative estimate of the computed current velocity.

DISCUSSION

Although dissolved salt contributed to the density structure of the lake in the past (Rattray, Seckel and Barnes, 1954), 20 chlorinity determinations showed that any contribution to the density structure was small. The maximum chlorinity increase from the surface to the bottom at four deep stations was 0.003. This would cause a change in the density equivalent to a temperature change of 0.1° C. One station off Leschi Park on 18 February had a maximum chlorinity difference in the water column of 0.009 per mille. The chlorinity was never greater than 0.011 per mille; the average was 0.004 per mille.

The observed heat loss in the Sand Point-Juanita Bay section was compared to the calculated heat budget (fig. 13). The observed heat loss in the section was about 20 percent smaller than the computed heat loss. There are three possible reasons for this discrepancy:

(1) the heat budget equations become less accurate as shorter periods are considered,

(2) the change in heat content from one day to another is a small difference between two large numbers,

(3) there may be a loss of cold water through the lateral boundaries of the section at depth.

The third alternative seems to be the most probable. Anderson (1954) said that the accuracy of the heat budget for periods greater than 7 days is ± 5 percent. Allowing for the greater accuracy of meteorological data, the heat budget for a period of 22 days should be accurate to at least ± 10 percent. The accuracy of the observed heat change also increases as longer periods are considered.

It is proposed that the computed current be increased by 20 percent to compensate for the water that flows out of the sides of the section at depth. The average flow velocity would then be about 2 cm/sec.

Assuming an average heat loss of 300 cal/cm^2/day, the top 5 m of the lake would cool at a rate of 0.6° C/day. A flow of 2 cm/sec would cause complete replacement of the water in Juanita Bay in 1.5 to 2 days. In that time a parcel of water is in the bay would cool 0.9° C to 1.2° C. Such cooling corresponds well with the observed temperature decrease in Juanita Bay.

CONCLUSIONS

The bottom water in Lake Washington is formed in the many shallow bays that surround the lake. The bays temporarily confine the water as it cools, allowing it to become denser than the water in the main body of the lake. The cold, dense water then flows out of the bay and down the slope, mixing with and displacing the original deep water, resulting in a bottom layer of nearly uniform temperature.

The shape of a cross section determines in part whether that section has an observed heat loss which is greater or less than the surface heat loss computed from the heat budget. Water from sections with extensive shallow areas will flow out of those sections into the deep parts of adjacent sections that do not have large shallow areas. Continuity requires a return flow at some other depth, probably near the surface. Because of this removal of cold water from the section in which it was formed, sections with large shallow areas will not become as cold as expected when heat loss is computed from meteorological conditions. Similarly, sections without extensive shallow areas will become colder than expected, because of the lateral influx of cold water and loss of warmer water.

Correcting for the escape of cold water through the sides of the Juanita Bay section, the estimate of the current velocity was 2 cm/sec.

Future studies should include cross sections off both shallow embayed areas and steep-sided areas off straight shores. They should also include routine sections to give a better picture of movements along all axes. This however, would require more than one vessel and

was not considered within the scope of the present exploratory work. In areas where the flow is concentrated, as off the mouth of a bay, a dye tracer could be used to follow water parcels and get additional information for estimating water velocities.

TABLE I

AVERAGE DAILY WIND FOR THE WARMING CYCLE, 2 FEBRUARY TO 24 APRIL 1963

Date	Wind m/sec	Date	Wind m/sec	Date	Wind m/sec	Date	Wind m/sec
2 Feb.	2.3	23 Feb.	1.5	16 Mar.	1.6	5 Apr.	2.3
3	5.6	24	0.9	17	2.6	6	3.5
4	4.3	25	2.3	18	5.3	7	1.4
5	1.4	26	5.9	19	3.7	8	2.1
6	2.4	27	1.4	20	1.3	9	1.6
7	1.7	28	3.9	21	3.3	10	2.0
8	1.2	1 Mar.	3.8	22	3.4	11	3.0
9	2.8	2	2.3	23	2.0	12	2.1
10	2.7	3	1.5	24	1.8	13	2.2
11	1.8	4	1.0	25	1.3	14	3.2
12	2.5	5	2.0	26	1.3	15	6.0
13	1.8	6	1.9	27	1.4	16	2.5
14	0.8	7	2.2	28	6.2	17	1.6
15	0.8	8	1.6	29	5.4	18	3.3
16	0.9	9	1.8	30	5.6	19	2.5
17	2.2	10	1.8	31	3.7	20	1.9
18	0.5	11	3.6	1 Apr.	1.9	21	2.4
19	2.4	12	1.3	2	0.7	22	5.1
20	0.6	13	3.1	3	2.5	23	4.2
21	1.0	14	4.2	4	3.3	24	2.5
22	1.3	15	5.0				

TABLE II

METEOROLOGICAL DATA USED IN THE HEAT BUDGET CALCULATIONS

Date	Water Temp. °C	Air Temp. °C	Dew Point °C	Wind Speed m/sec	Cloud Cover tenths
10 Jan.	8.30	-3.0	-14.5	4.8	0
11	8.10	-6.2	-18.2	2.8	0
12	7.94	-4.3	-12.4	1.3	4
13	7.86	-0.6	- 5.1	1.5	10
14	7.78	2.8	2.0	1.2	10
15	7.73	5.8	5.6	1.3	10
16	7.68	4.8	3.9	1.0	10
17	7.64	4.4	3.5	1.8	10
18	7.59	3.1	- 4.7	3.1	3
19	7.54	0.0	- 5.6	0.7	6
20	7.49	1.5	- 3.1	1.3	6
21	7.45	0.8	- 0.5	0.8	8
22	7.41	2.9	1.7	1.5	6
23	7.37	2.3	- 1.4	1.6	8
24	7.33	2.0	0.4	1.0	10
25	7.29	3.3	0.7	2.0	5
26	7.21	0.6	- 3.2	1.5	7
27	7.14	-0.6	- 3.4	1.1	7
28	7.02	-0.1	- 7.7	4.1	5
29	6.90	-0.9	-17.2	2.8	1
30	6.80	-1.4	- 8.7	2.6	9
31	6.74	0.8	0.1	2.1	10
1 Feb.	6.75	3.0	2.3	1.4	8

TABLE III

TERMS OF THE HEAT BUDGET EQUATION
$Cal/cm^2/day$

Date	Q_s	Q_r	Q_b	Q_e	Q_h	Net Out	Observed Heat Loss
10 Jan.	161	22	231	332	257	681	
11	164	22	224	261	246	589	
							440
12	146	20	160	179	160	373	
							198
13	30	5	50	145	115	285	
							198
14	26	4	45	73	63	159	
							115
15	20	3	44	22	25	74	
							115
16	50	7	45	38	35	75	
							115
17	20	3	46	61	46	146	
							115
18	176	23	177	183	81	288	
							115
19	107	15	119	119	86	232	
							115
20	144	20	116	116	78	186	
							115
21	44	6	76	83	76	197	
							143
22	70	10	106	76	60	182	
							143
23	170	23	82	109	72	177	
							143
24	32	5	46	80	65	164	
							143
25	142	19	126	92	59	154	
							244
26	131	18	98	117	88	190	
							244
27	120	17	99	118	133	247	
							260
28	181	24	141	221	148	353	
							260
29	215	28	234	224	132	403	
							379
30	57	8	71	179	136	337	
							124
31	33	5	46	92	89	199	
							70
1 Feb.	80	11	75	57	51	114	

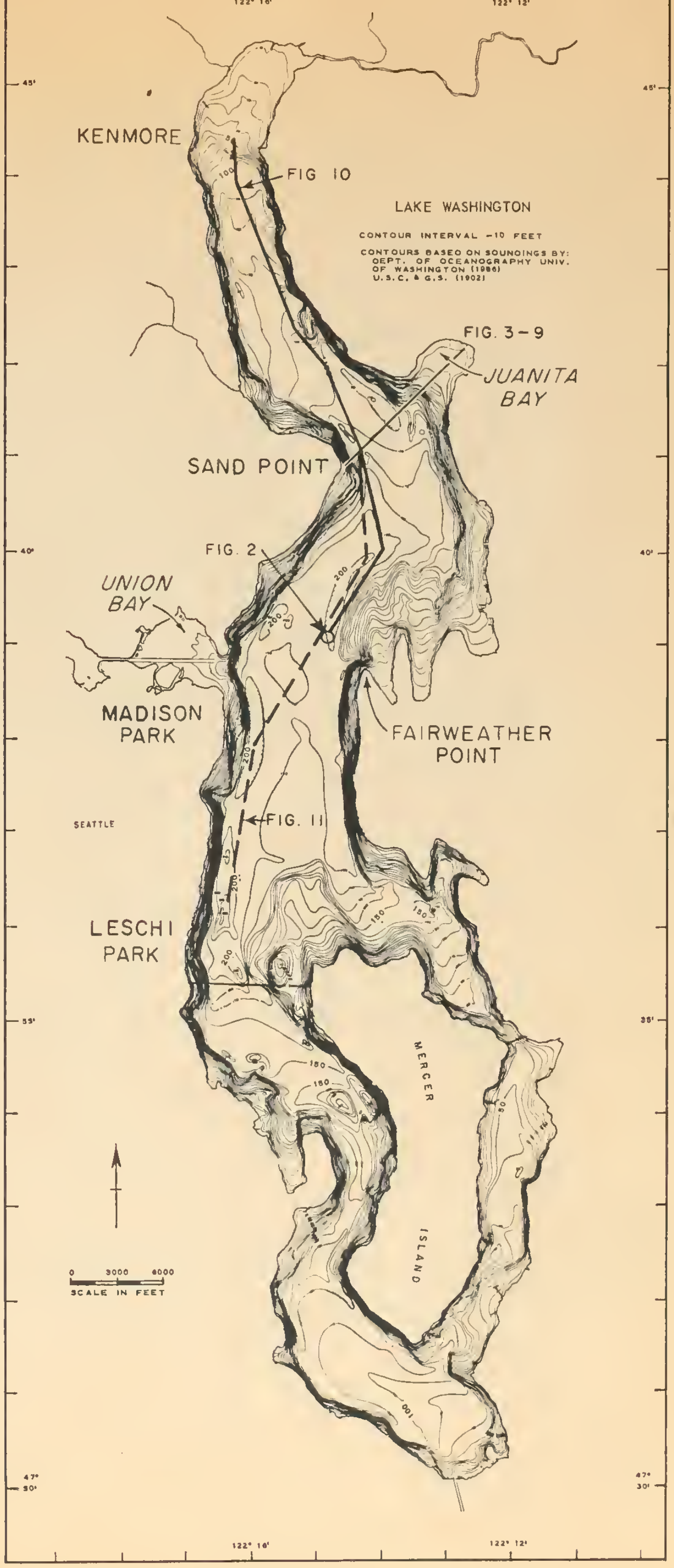

FIGURE 1. The bottom topography of Lake Washington and the location of the various sections.

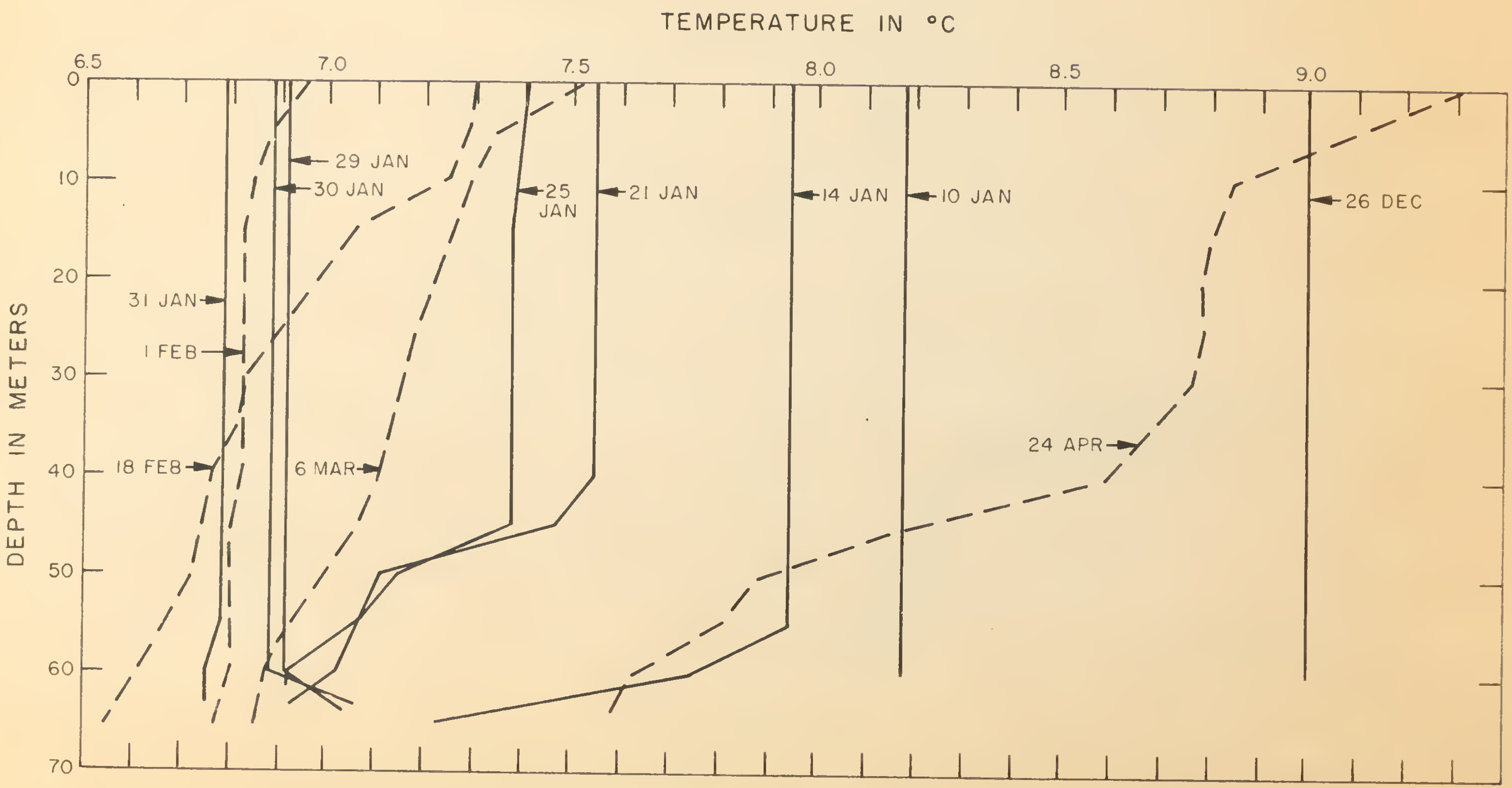

FIGURE 2. The vertical temperature structure off Fairweather Point at various times during the winter of 1962-63.

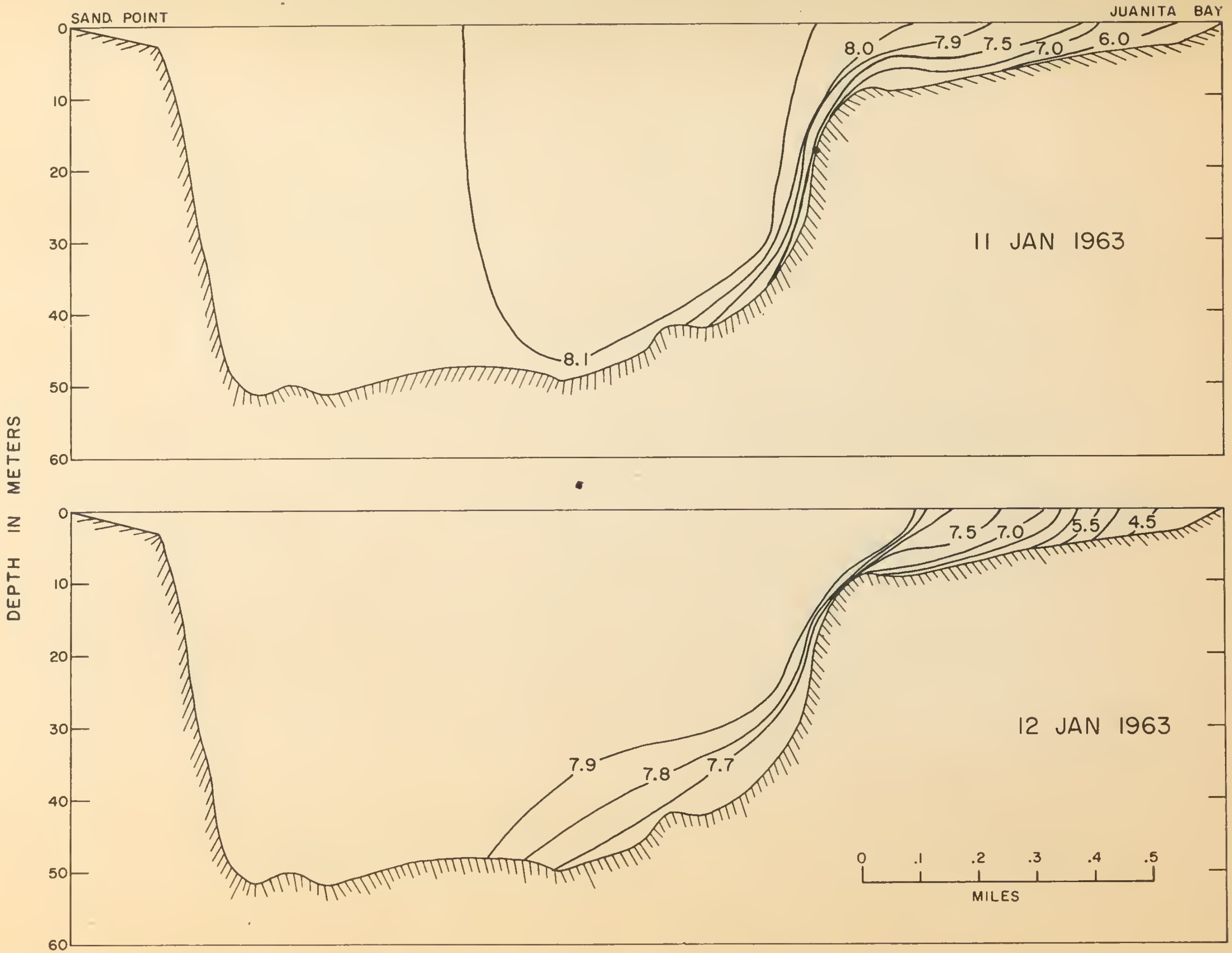

FIGURE 3. Temperature profile from Sand Point to Juanita Bay for 11 and 12 January 1963

FIGURE 4. Temperature profile from Sand Point to Juanita Bay for 14 and 21 January 1963

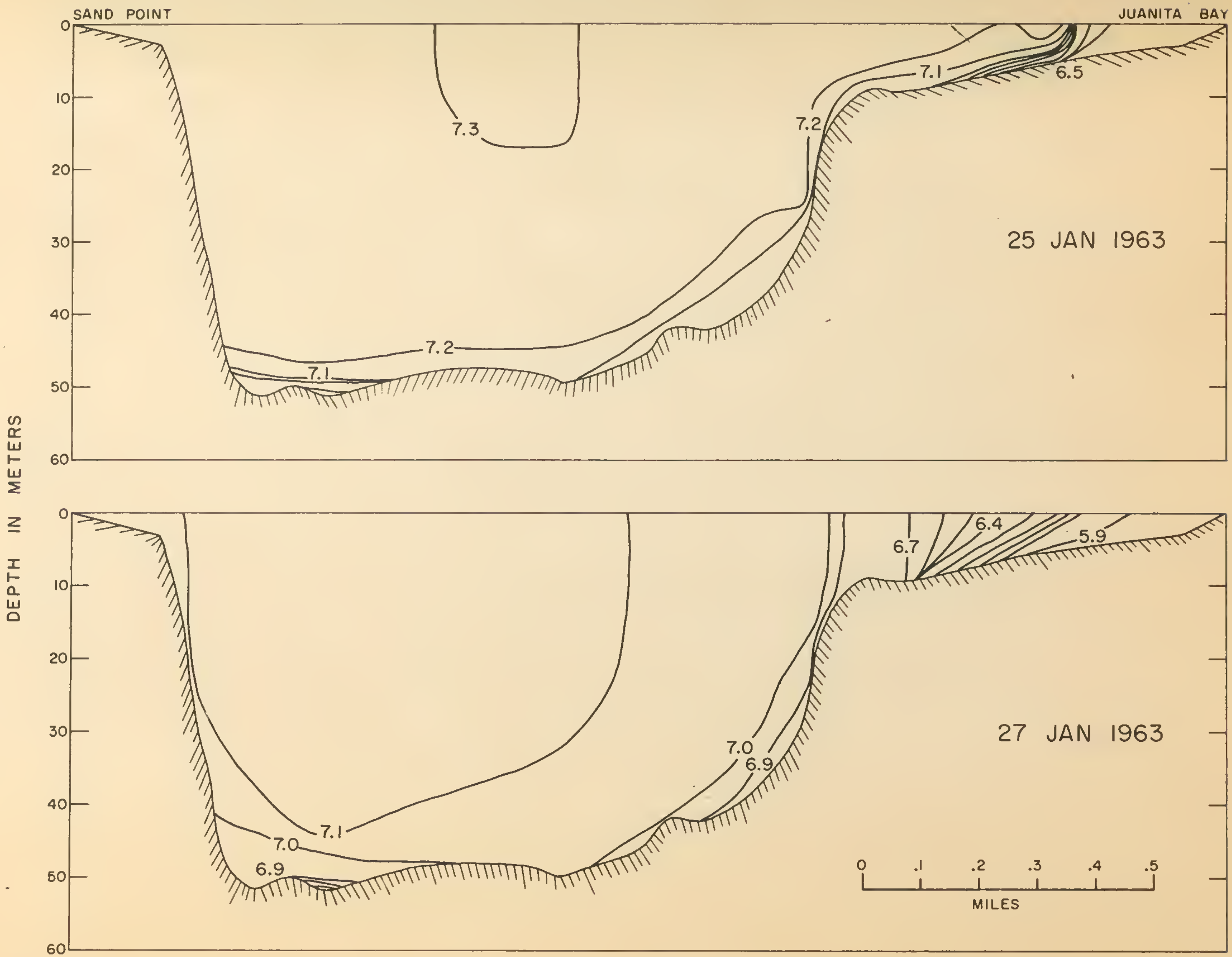

FIGURE 5. Temperature profile from Sand Point to Juanita Bay for 25 and 27 January 1963

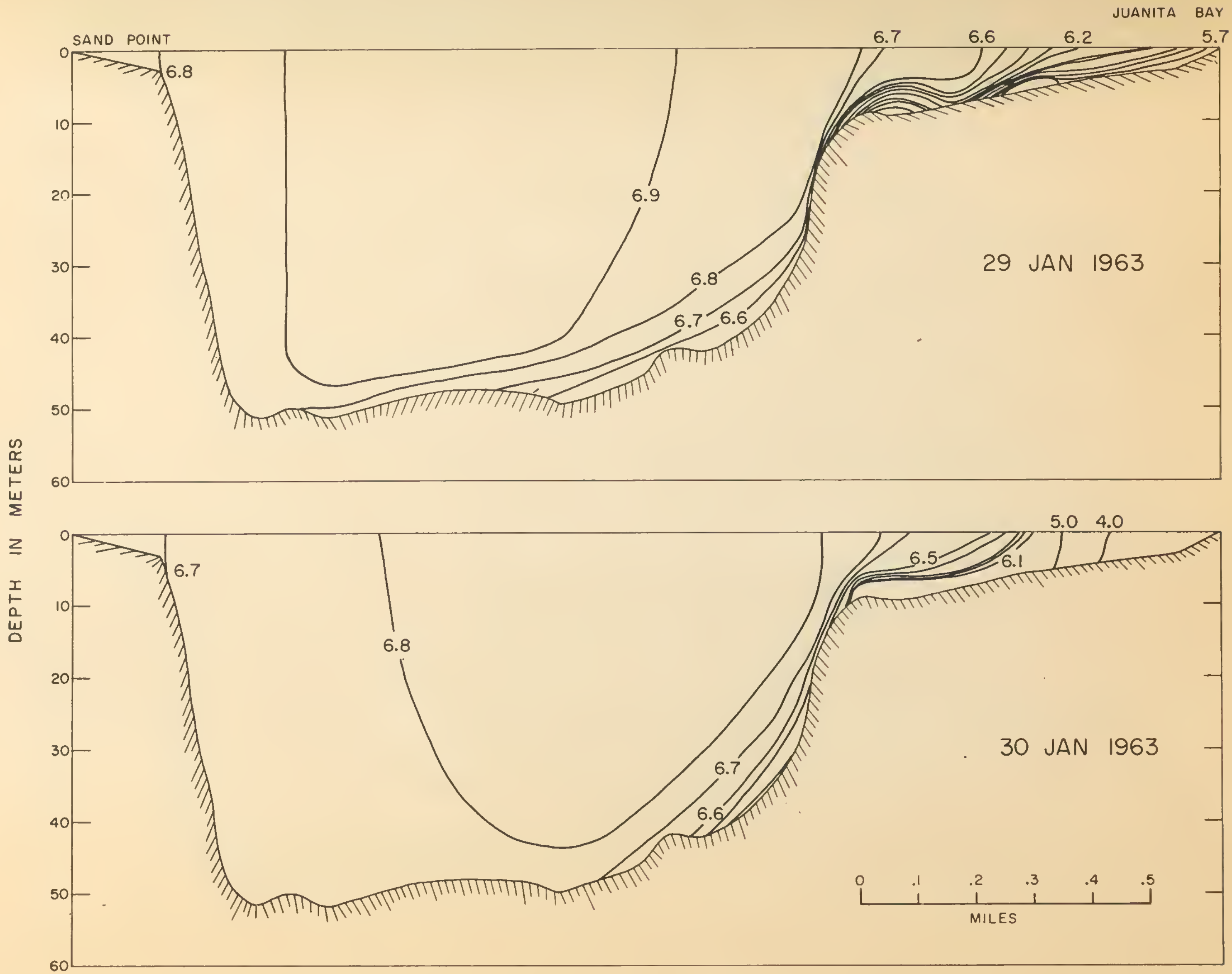

FIGURE 6. Temperature profile from Sand Point to Juanita Bay for 29 and 30 January 1963

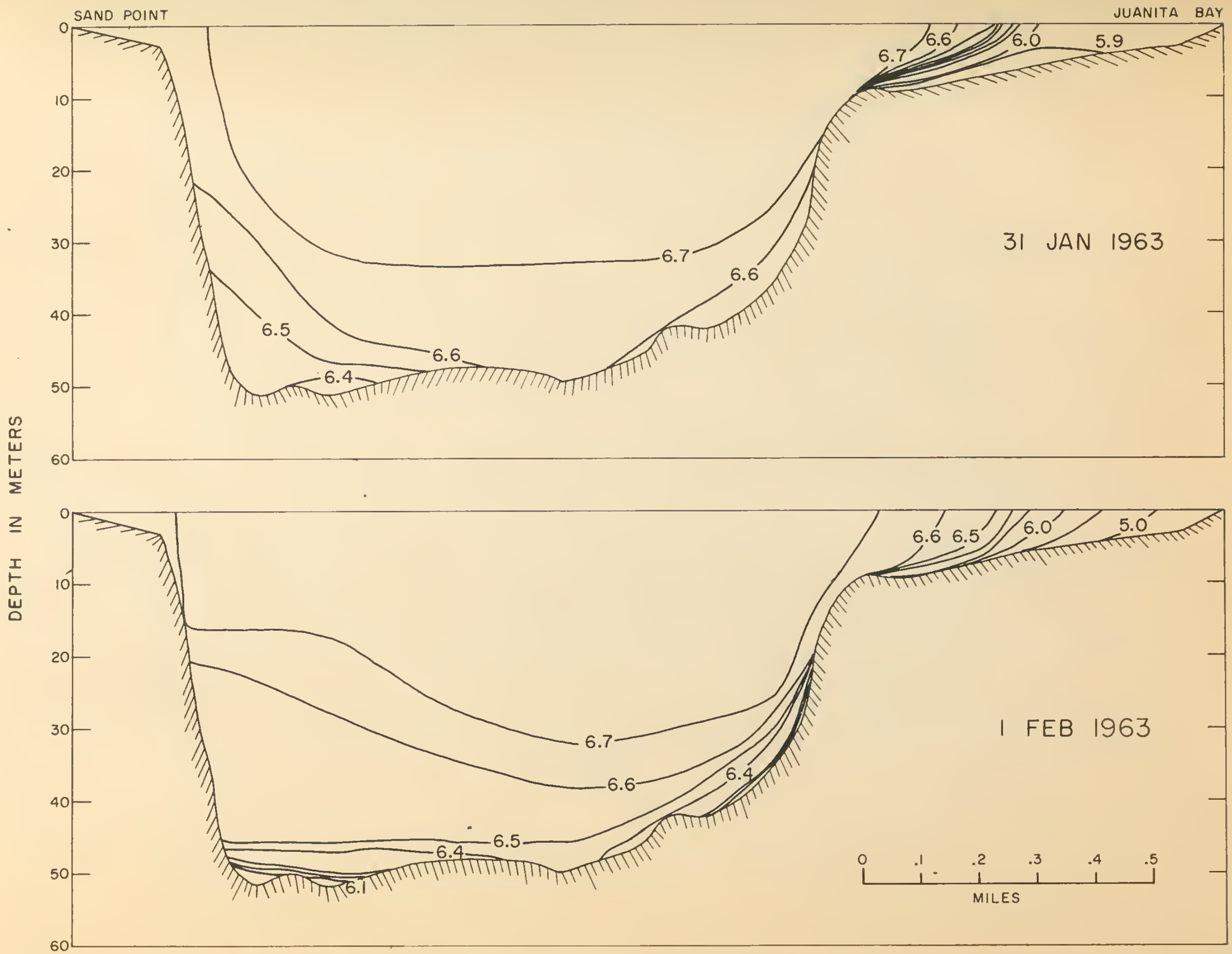

FIGURE 7. Temperature profile from Sand Point to Juanita Bay for 31 January and 1 February 1963

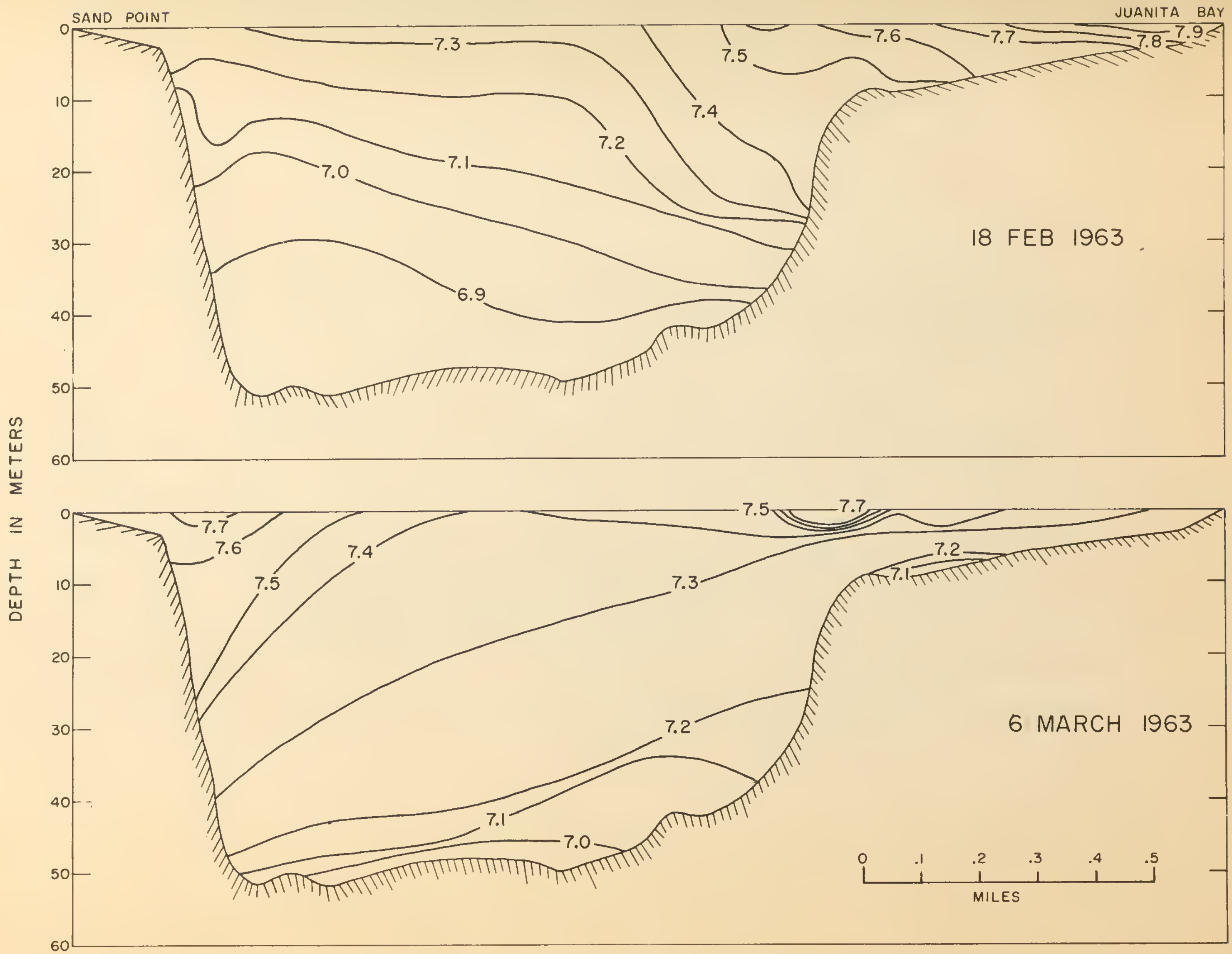

FIGURE 8. Temperature profile from Sand Point to Juanita Bay for 18 February and 6 March 1963

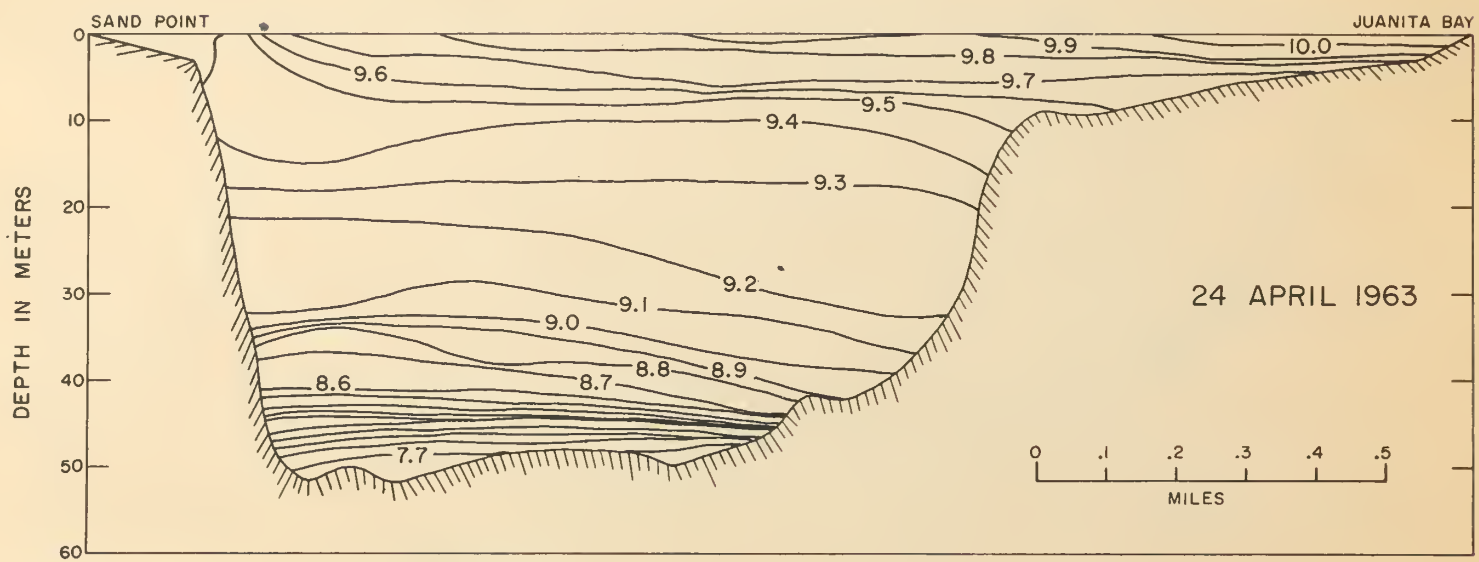

FIGURE 9. Temperature profile from Sand Point to Juanita Bay for 24 April 1963

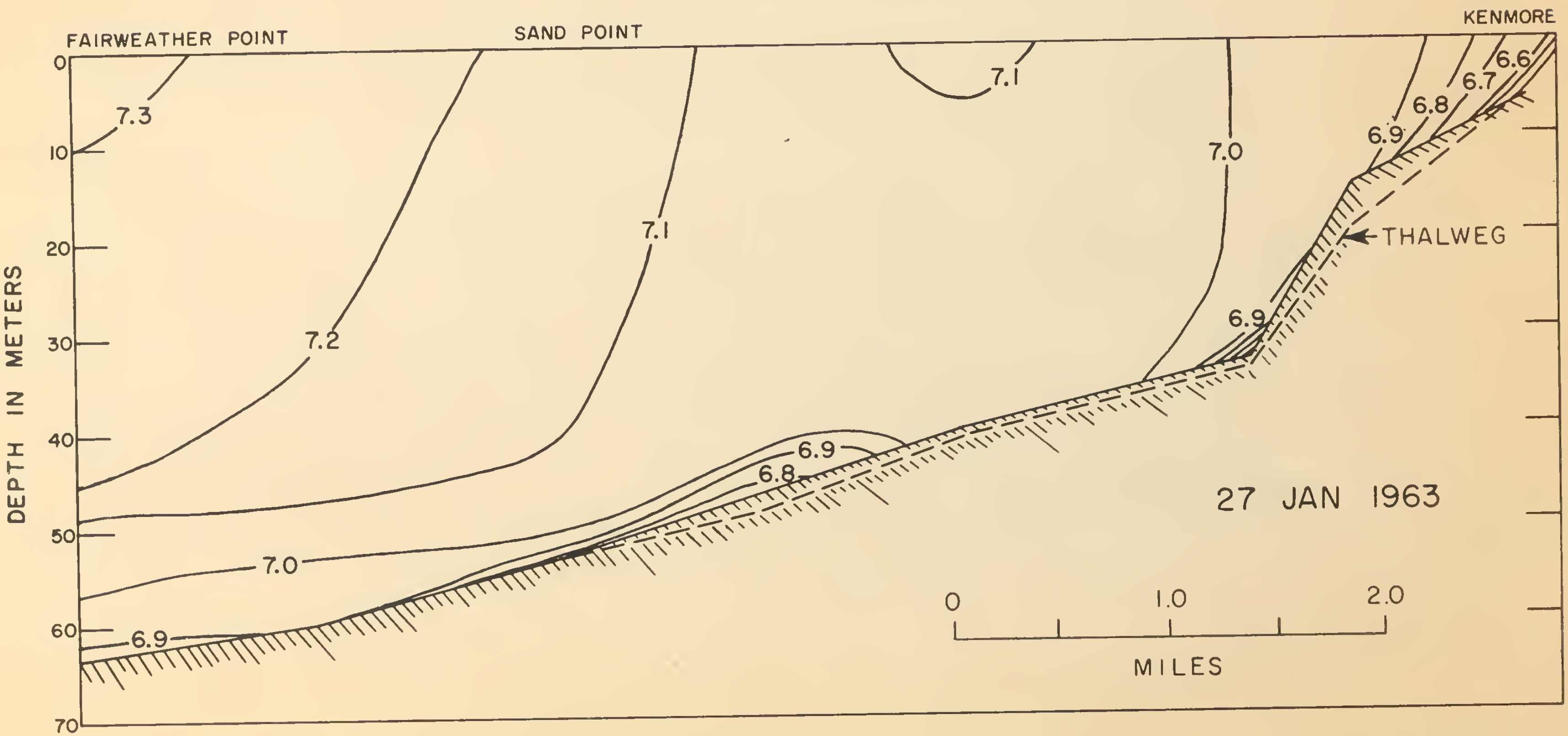

FIGURE 10. Temperature profile from Kenmore to Fairweather Point on 27 January 1963. The thalweg is shown as a dashed line.

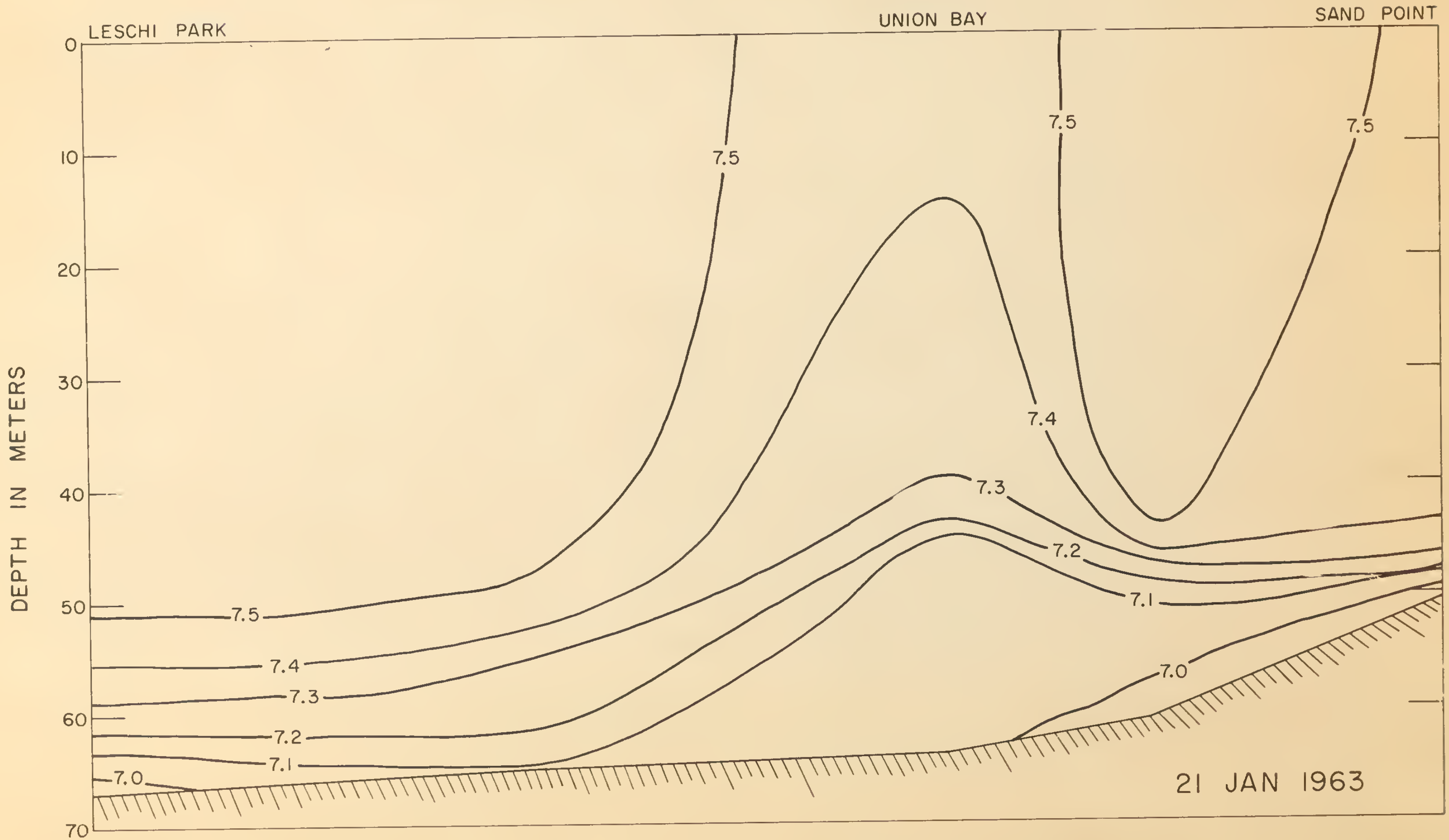

FIGURE 11. Temperature profile along the axis of the lake from Sand Point to Leschi Park on 21 January 1963

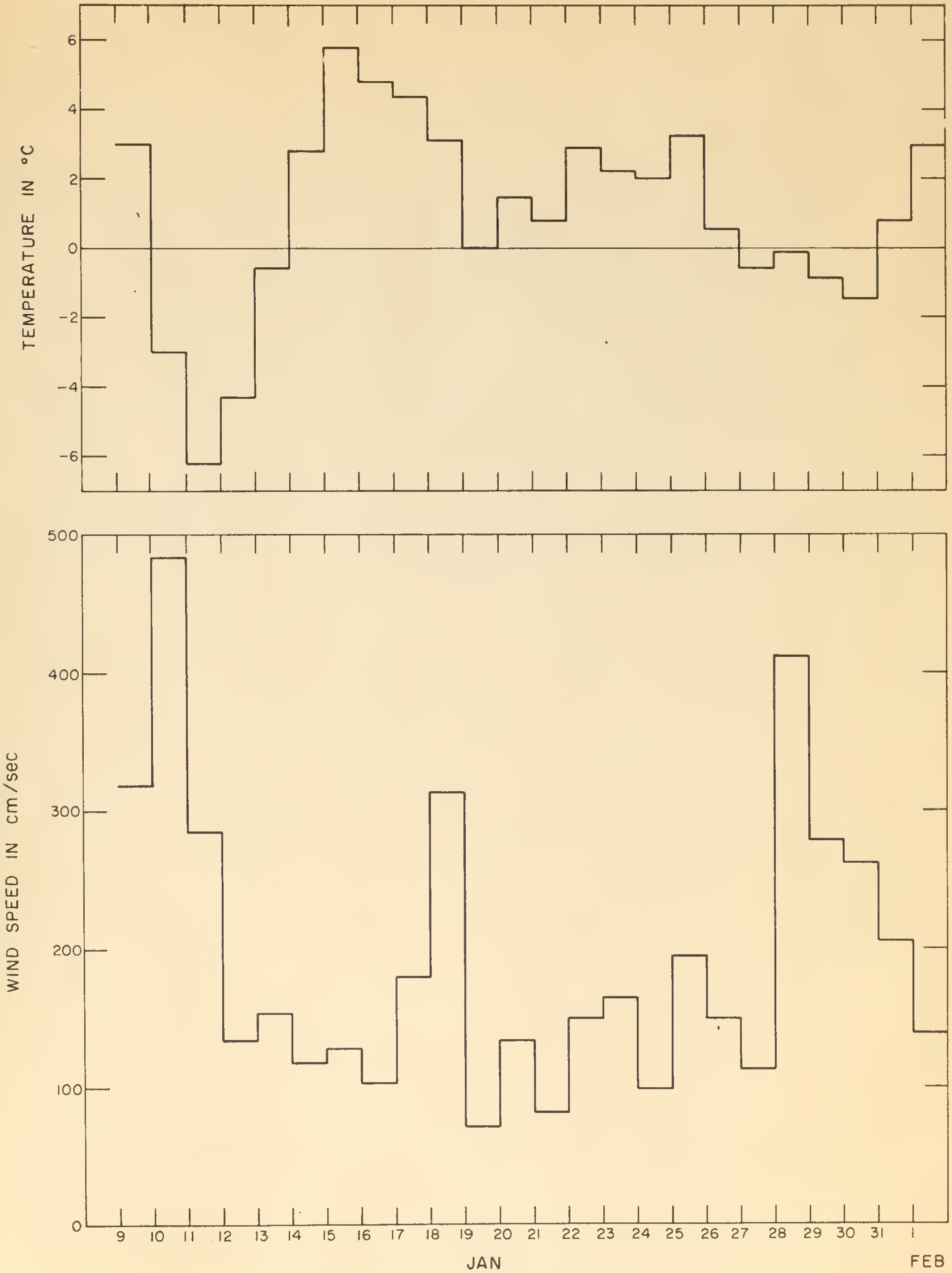

FIGURE 12. Top: Daily average air temperature at Sand Point.
Bottom: Daily average wind speed at Sand Point.

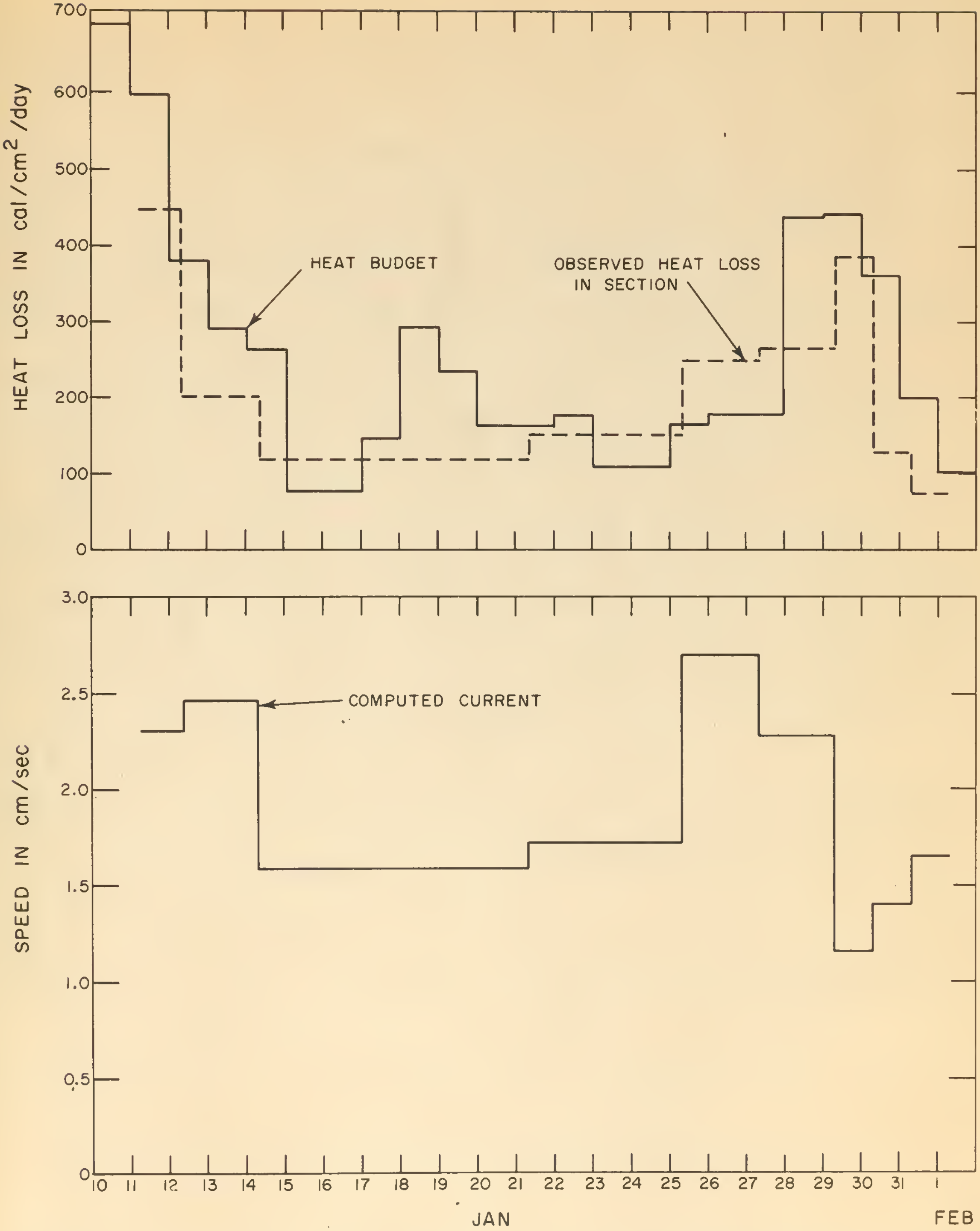

FIGURE 13 Top: Heat loss computed from the heat budget and the observed heat loss in the Sand Point - Juanita Bay section.
Bottom: Computed current in the Sand Point - Juanita Bay section.

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