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SYNOPTIC TEMPERATURE MEASUREMENTS OF A GLACIER LAKE AND ITS ENVIRONMENT

By

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON, D.C. 20242

Interagency Report
NASA-107

Mr. Robert Porter
Program Chief
Earth Resources Survey
Code SAR, NASA Headquarters
Washington, D. C. 20546

Dear Mr. Porter:

Transmitted herewith is one copy of:

INTERAGENCY REPORT NASA-107

SYNOPTIC TEMPERATURE MEASUREMENTS OF A GLACIER LAKE
AND ITS ENVIRONMENT

by

William J. Campbell[1]

Sincerely yours,

William A. Fischer
Research Coordinator
Earth Orbiter Program

1/ U.S. Geological Survey, Tacoma, Washington
Contract No. R-146-09-020-006
Task No. 160-75-01-61-10

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Synoptic Temperature Measurements of a Glacier Lake and its Environment

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Abstract

Temperature measurements of a small (area = 20.0 hectares), high (altitude = 1,620 m) lake located at the terminus of South Cascade Glacier, Washington, and its ice and rock environment were made with infrared radiometers (8-14 μ range) during various meteorologic regimes. By making simultaneous measurements of lake surface temperatures with four sensors it was found that the "cold skin" effect occurs -- that is, the radiometric temperature is cooler than that measured at the surface by thermistors, thermopiles, and thermometers. The meteorological situation most favoring the development of the "cold skin" is a strong, dry drainage wind with clear skies. Temperature distributions of the lake surface and its background were mapped by remote infrared sensing from adjacent ridges. By correcting for reflectivity and emissivity changes, accurate synoptic maps of the lake surface temperature were obtained. It was found that the shallow, stable surface layer adjusts rapidly to changes in the drainage and valley winds. Several surface temperature maps obtained during periods of strong drainage winds compare well with an infrared image obtained from an aircraft, showing a warm sector at the lake exit separated by a temperature front of high gradient from a cool sector having gradually cooler temperatures towards the glacier terminus. At times of no wind over the lake the surface temperature was uniform except for a narrow mixing zone at the glacier terminus. The warm sector was transported to the glacier terminus end of the lake by valley winds and a high gradient temperature front formed between it and the terminus mixing zone.

Introduction

Energy balance studies of glaciers are severely hampered by the lack of information on the spatial and temporal variation of surface temperature over the glacier. Remote sensing in the infrared region offers a feasible means of obtaining this information. In an effort to test the possibility of making such measurements, experiments were performed on a glacier lake and its rock and ice environment. A lake is a plane surface where changes in surface emissivity and reflectivity due to oblique sensing can be handled far more easily than on an undulating glacier surface of varying surface structure and roughness. This study was also done as a part of a combined heat, ice, and water balance study of the South Cascade Glacier drainage basin, a contribution to the International Hydrologic Decade (IHD). It thus may have application to other combined balances projects of the IHD.

The recent development of infrared radiometers has made it possible to obtain truly synoptic temperature measurements of snow and water surfaces and to study micro and mesoscale features of water circulation which can provide much cause-and-effect information on features of similar scale in the atmosphere. Much work has been done over the oceans with airborne radiometers (Saunders and Wilkins, 1966; Wendland and Bryson, 1966) in which scan lines of surface temperature were obtained over paths with lengths of hundreds of kilometers, but little work has been done on lakes and on mapping temperatures in detail over smaller areas.

South Cascade Lake is a small (area - $2 \times 10^5 m^2$), high(altitude = 1,620 m) lake located at the terminus of South Cascade Glacier, Washington. The lake bottom resembles a crescent-shaped saucer, and its greatest depth is 60 m (see figure 1). In the summers of 1966 and 1967 radiometric observations were made on South Cascade Lake, using Barnes IT-3 and PRT-5 infrared radiometers operating in the 8-14μ range, along with a variety of limnological and meteorological observations.

In situ measurements

During the winter the lake is covered with approximately 50 cm of ice and 3 m of snow, and its temperature is below the temperature of maximum density (4°C) with an ice-water interface temperature of 0°C rising sharply to 1.2°C at 10 m depth and gradually rising to 2.5°C at 30 m depth and remaining at that temperature at greater depths. When the ice and snow cover melts off, usually in early August, the temperature profile quickly approaches the 4°C turnover temperature. When this point is reached a warm, shallow (1-4 m), highly stable layer develops on the surface while the water at depth remains at 4°C. This condition persists until the onset of fall snowstorms.

The radiometric observations were performed in the period prior to the spring turnover time and during the growth and maturity of the stable layer. The demise of the stable layer was not observed because it occurs during the fall storms when infrared radiometric observations are difficult.

The in situ surface temperature measurements were made from a small boat at numerous points in the lake using four sensors simultaneously; an infrared radiometer (IT-3 or PRT-5) mounted 2 m above the surface pointing vertically down; a three-point thermopile with each point mounted on separate floats which were set so that the submerged thermocouples would at no time break through the air-water interface; a thermistor probe mounted in a similar fashion; and a bucket with a mercury thermometer. The thermistor and thermopile were shielded from solar radiation.

More than a hundred sets of surface temperature measurements were obtained under various meteorological conditions at different points on the lake. Some of these observations are given in Table 1. In all cases the thermopile and thermistor surface temperatures agree closely, generally within 0.1°C. Although the thermocouples were small (size 40, copper-constantan) and the mass of the individual floats was minimal, it was impossible to keep the thermopiles just under the surface -- even capillary waves caused the sensors to sample a layer several millimeters deep. The thermistor probe was five times the diameter of the thermocouples and therefore sampled a deeper layer, which may explain why the thermistor generally gave slightly warmer temperatures than the thermocouples.

An interesting feature is that the radiometric surface temperature is usually cooler than the thermocouple and thermistor temperatures. This difference is as much as 2.2°C, with an average of 1.4°C. This "cold skin" has been noted by Hasse (1963) who estimates that its effect probably has been overestimated on sea surface studies. Saunders and Wilkins (1966) compared radiometric temperature measurements taken from aircraft with bucket temperatures. By correcting their radiometric temperatures for absorption and emission of the atmosphere and for reflected sky radiation (neither of which corrections had to be made here because the radiometer was mounted close to the water and shot vertically), they found close agreement, within a few tenths of a °C, between the radiometric and bucket temperatures. In the present study, the bucket temperatures were generally a few tenths of a °C cooler than the thermocouple and thermistor temperatures, which probably results because the bucket samples a layer 30-50 cm deep and this catches cooler water from within the stable layer. However, the bucket temperatures were warmer than the radiometric temperatures in most cases, with an average of 1.2°C. The only cases where they agree occurred during periods of strong insolation and no wind, and it was in these cases that the closest agreement between all four temperature measurements occurred. The meteorological situation most favoring the development of a "cold skin" appears to be a strong, dry drainage wind with clear skies. The data indicate that the "cold skin" is a common feature of a glacier lake, and that it is probably a consequence of evaporation and heat exchange at the surface.

The radiometric temperature readings given in Table 1 are average readings usually spanning 15-30 seconds. During many of the observations rapid temperature fluctuations occurred. The field of view of the radiometer during these measurements was a circle with a diameter of 10 cm. The response time of the radiometer is sufficiently short (50 milliseconds to 63 percent) that the fluctuations may indicate real temperature variations of the water surface. In most cases these fluctuations were of the order of magnitude of a few tenths of a °C, but in one case rapid fluctations as large as 1°C occurred. Perhaps the "cold skin" is generated in a spotted or banded array. These fluctuations were not observed when the water surface was sensed from the ridges, where the field of view of the radiometers was an ellipse with a minor axis of at least 3.5 m and each observation gave a surface temperature averaged over an area of the order of 10 m^2. From this it is apparent that the individual spots or bands in the "cold skin" array are at least an order of magnitude smaller.

Oblique sensing of lake and environment

A key idea in this study was that since it was not possible to obtain spatial and temporal variation of the surface temperature of the lake in sufficient detail utilizing aircraft it might be possible by making observations from high peaks bordering the lake if one were able to allow for emissivity and reflectivity changes resulting from oblique scanning. McSwain and Bernstein (1961) have shown that the reflectivity of water in the range of 8-14μ increases sharply when the angle of incidence exceeds the 60°. No observation point above the lake afforded a view of all parts of the lake with angles of incidence less than 60°, and it was realized that for each area observed radiometrically on the lake it would be necessary to also observe the radiometric temperature of the reflected area in space. The true surface temperature could then be calculated using

$$R = \varepsilon(\phi)\sigma T^4 + [1 - \varepsilon(\phi)]R' \qquad (1)$$

where R is the radiance observed, $\varepsilon(\phi)$ is the emissivity of the water surface as a function of angle of incidence ϕ, σ is the Stephan-Boltzman constant, T is the surface temperature, and R' is the radiance of the reflected area in space.

A grid of tethered floats served as target points for the radiometric temperature observations. Forty data points were selected for the synoptic coverage. For each point, the area of the background reflected in the sensing view was accurately surveyed. Thus for each synoptic temperature map 80 observations were necessary, and after much practice the time required to map the lake and background radiances was reduced to 5 minutes, including calibration shots. Although rapid changes in the temperature of the lake surface were found to occur, the 5-minute sensing time can be said to be sufficiently small to afford a synoptic view of its distribution. The emissivity of the rock cliff in the background was not measured, but that of rocks of similar type not far from the area in question was measured by Buettner, Katsaros, and Kreiss, (1965) and was found to be 99 percent in the 8-14μ range.

Initially, simultaneous measurements of the radiometric temperature of the water surface were made from a boat and from a ridge 100 m above the lake. It was found that by correcting for the reflected radiation from the rock cliff according to (1) the remote observation agreed with the in situ observation to within 0.5°C, which was considered to be a tolerable error limit. Another check on this technique was made by performing similar radiometric scanning from a ridge at the turnover time of the lake, that is when the cool surface layer was warmed to the 4°C maximum density temperature causing vertical currents that mix the entire lake to that temperature. By sensing the entire lake surface at its turnover time when no wind was blowing and a dense cloud cover existed, thus when the "cold skin" effect was minimal, it was possible to check the above technique for a variety of rock cliff temperature patterns.

The lake surface temperature was mapped from two ridges under a variety of meteorological conditions, and it was found that many features of its spatial and temporal variations could be accurately and quickly observed. The stable surface layer adjusts rapidly to changes in the wind, and since drainage or valley winds flow over the lake most of the time its surface temperature distribution is rarely uniform. Rather, it is characterized by temperature fronts of surprisingly high gradients. Consider figure 2 which shows the greatest temperature range observed during the study. Near the glacier terminus, where 0°C water enters the lake and quickly mixes, the surface temperature undergoes rapid changes, and the area of this mixing zone proved to be constant for all meteorological conditions. A stong drainage wind, which had been steadily blowing for several hours prior to observation time, pushed the warm, stable surface layer to the far end of the lake and formed a temperature front with a gradient of 6°C/150 m. Bear in mind that two mechanisms probably acted to create this front. First, the major one of the frictional driving of the wind which stripped the stable layer from the glacier terminus end of the lake and piled it up at the far end. Second, a minor, but I believe significant mechanism, in the drainage wind situation the surface wind was always at greater velocity in the terminus area than at the lake exit area, thus it is highly probably that a differential "cold skin" effect occurred in which the cool sector shown in figure 2 experienced a greater cooling than did the warm sector. Logistical limits prevented simultaneous remote radiometric sensing and surface wind observations, but the differential wind velocity over the lake surface could always be seen by noting the wind driven capillary and small gravity waves.* This differential "cold skin" effect probably occurred in the valley wind case also. The morphology of the glacier valley is therefore probably a significant factor in the formation of the surface temperature structure of a glacier lake. An infrared image (not available for publication) of South Cascade Lake obtained from an aircraft compares well with figure 2.

The surface temperature distribution of the lake changes rapidly with changes in wind. Consider figure 3 in which is shown a series of radiometric temperature distributions mapped at half-hour intervals. At 1530 PST, 18 August 1966, a drainage wind formed a surface temperature distribution similar to that shown in figure 2. Shortly thereafter the wind changed to a valley wind, and by 1600 PST a great change in the temperature structure occurred. The warm sector of the exit end of the lake cooled slightly and was transported to the center of the lake; the front moved up the lake toward the terminus. By 1630 PST a strong valley wind transported the warm sector to the terminus area of the lake, and a high gradient front formed between the warm sector and the unstable mixing zone. This temperature distribution persisted until the wind changed direction four hours later.

The radiometric temperature of the centerline of the lake and the rock band reflected in it could be observed in less than a minute, and this was done for selected periods in an effort to get greater detail than possible with the 5-minute lake mapping time. In figure 4 are shown five centerline temperature profiles taken at 15-minute intervals. The temperature front developed rapidly and its gradient increased rapidly as it migrated towards the lake exit. The profile shown for 1110 PST is essentially the steady state profile for the 3.2 m/sec drainage wind and would compare well to one plotted from the centerline temperatures in figure 2.

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*In this study no allowance was made for the variation of the reflectivity of the water due to surface roughness. Most of the remote sensing was performed from point TP-2 (see fig. 2), and the wave fronts, both in the valley and drainage wind situations, were generally parallel to the line of view. Thus, any reflectivity changes due to roughness were minimal.

Conclusions

The surface temperature distribution of a glacier lake responds rapidly to changes in the wind. Besides the wind stress, the "cold skin" effect may be a significant factor in forming the observed surface pattern. The radiational balance of a glacier lake can be accurately determined only if small time scale synoptic data of the surface temperature are available, and radiometric infrared sensing from adjacent ridges is a feasible means of obtaining them. Such measurements of small lakes can provide information on energy balance, circulation, and their meteorological causes.

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Table 1.--Comparison of surface temperatures measured with four sensors

Time	Date	Temperature Radio-metric (°C)	Ther-mopile (°C)	Ther-mistor (°C)	Buck-et (°C)	Wind (m/s) (D-drainage V=valley)	*Air tempera-ture (°C)	* Relative humidity (Percent)	Cloud cover (tenths)
	1966								
1010	15 Aug	9.4	10.6	10.5	10.0	1.8 D	14.2	22	0
1035	do	12.4	14.0	14.0	13.7	4.6 D	14.3	22	0
0915	16 Aug	11.0	13.1	13.2	13.0	5.5 D	12.1	17	0
1300	do	11.2	13.2	13.2	12.9	6.8 D	16.0	18	0
2000	do	10.9	12.0	12.1	11.8	5.5 V	14.9	43	0
1400	17 Aug	9.0	9.2	9.2	9.0	0	12.2	45	10
0930	20 Aug	9.0	9.5	9.6	9.1	2.2 V	12.2	22	5
0950	do	9.4	10.8	10.9	10.6	2.5 V	13.0	21	5
1230	do	10.2	11.7	11.7	11.5	3.2 D	13.2	17	6
1630	do	10.0	12.2	12.4	12.4	3.5 D	12.9	15	3
2000	do	10.3	12.0	12.1	12.0	2.2 V	12.0	24	3
2345	do	10.3	11.5	11.5	11.3	4.5 V	12.2	28	5
	1967								
1000	1 Aug	2.2	3.6	3.6	3.2	3.6 V	14.1	30	4
1300	do	2.8	3.6	3.6	3.2	1.0 V	14.3	30	6
1430	do	3.2	3.6	3.6	3.2	0	11.1	11	6
1700	do	2.0	3.4	3.3	3.0	3.8 D	7.3	10	0
1830	20 Aug	9.2	10.9	10.8	10.0	2.1 D	13.0	15	0
1900	do	10.2	10.9	10.9	10.0	1.8 V	16.0	32	1
2000	do	10.3	10.7	10.8	10.1	0.2 V	16.1	33	3

*Measured at 2 m above the water surface.

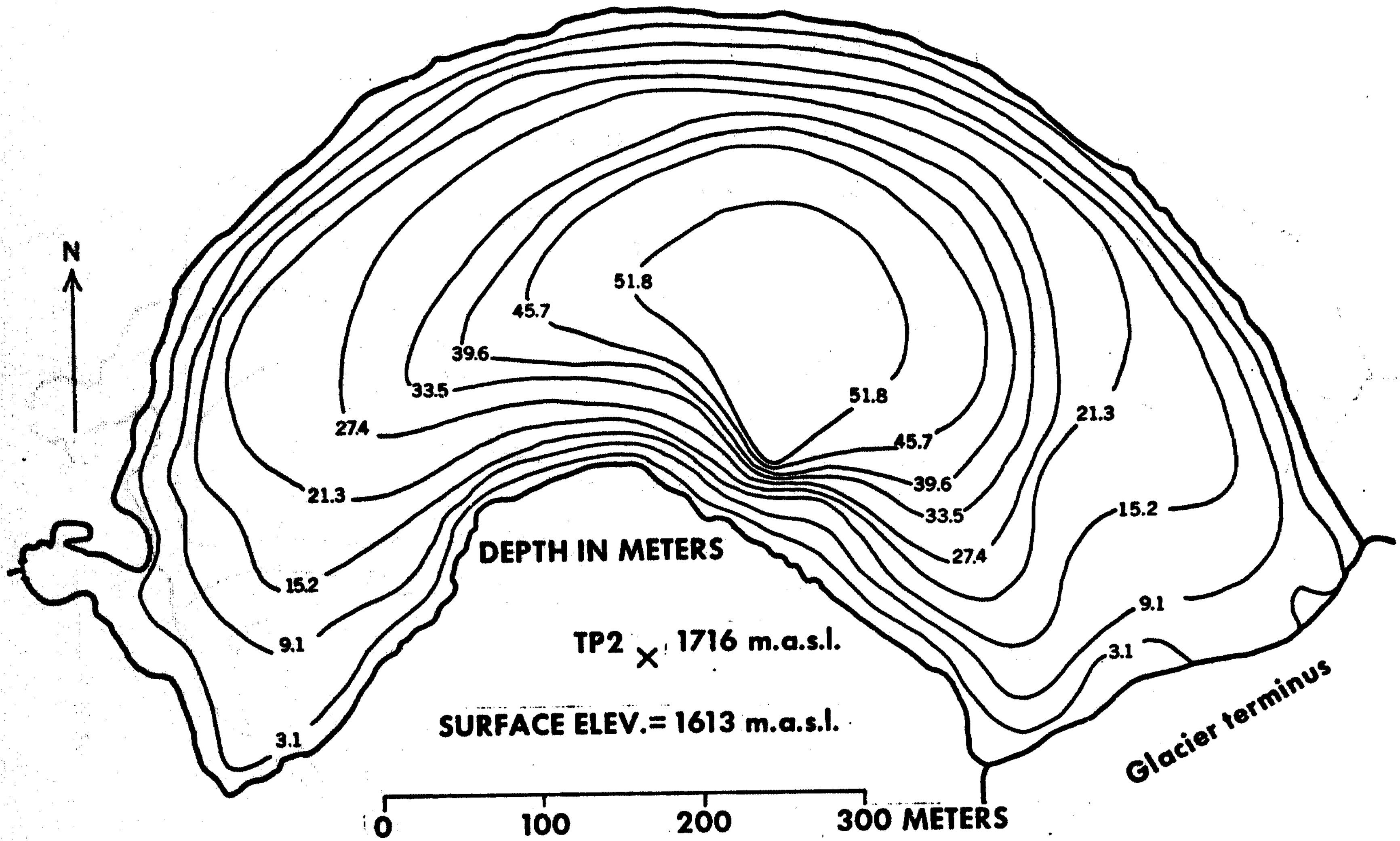

FIGURE 1 *BATHYMETRIC MAP* | SOUTH CASCADE LAKE

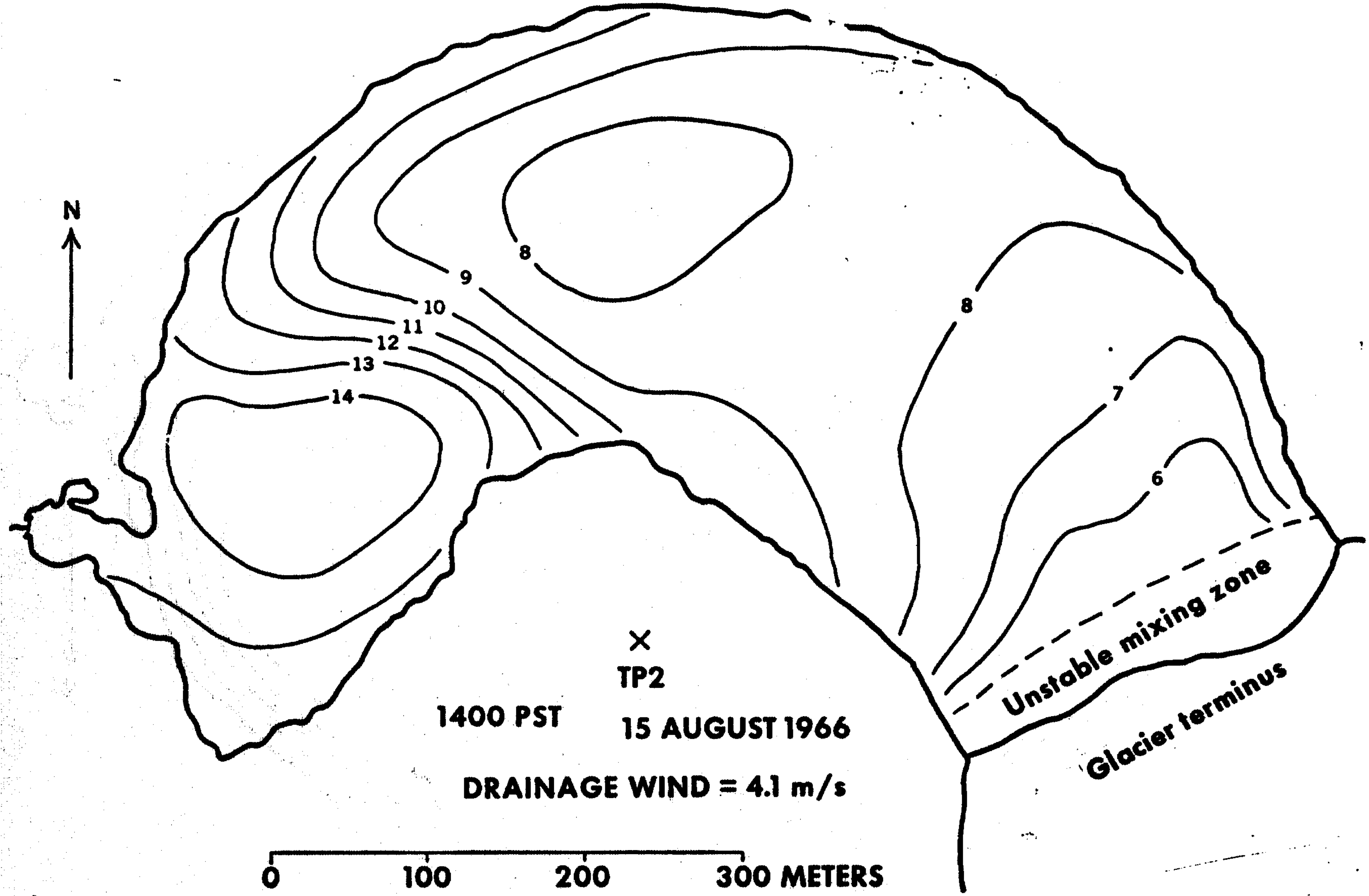

FIGURE 2 RADIOMETRIC TEMPERATURE (°C)

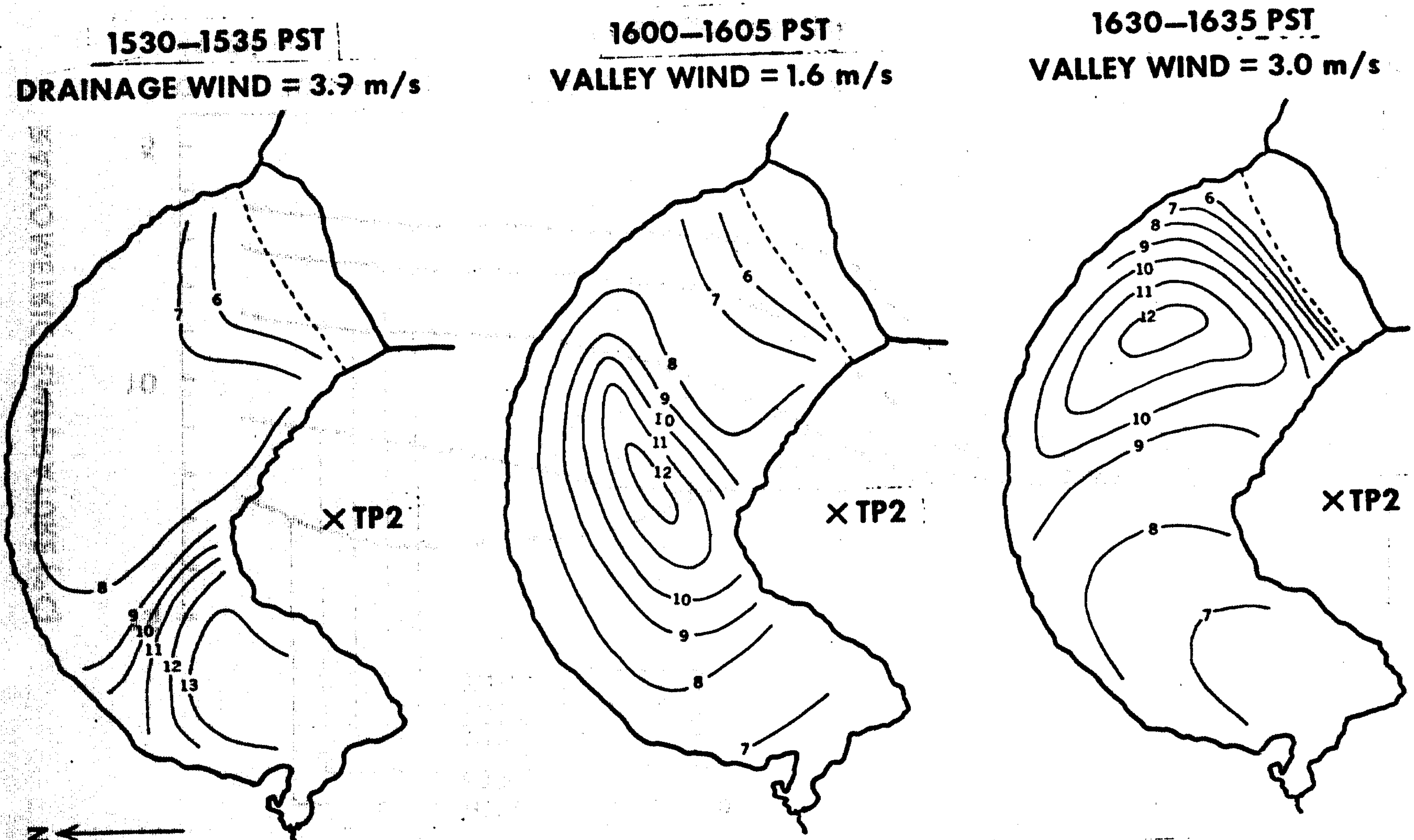

FIGURE 3 RADIOMETRIC TEMPERATURE MAPPED FROM TP2 (°C)
18 AUGUST 1966

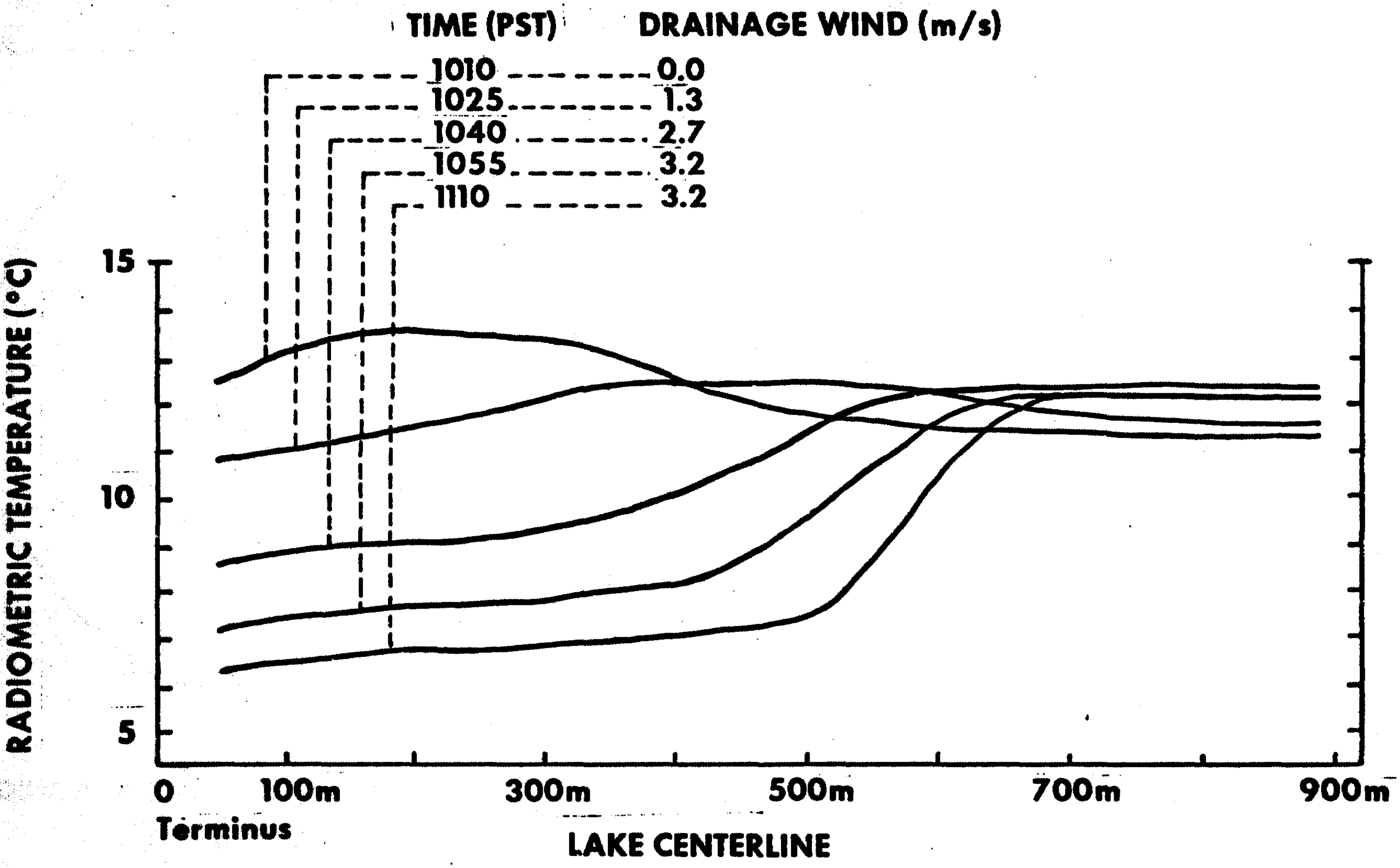

FIGURE 4 FRONT DEVELOPMENT | 19 AUGUST 1966