ist dieses Gebiet die einzige Stelle in der gesamten Antarktis, in der sich ein zweites lokales Zentrum entwickeln konnte. Eine Stauwirkung der Gebirge ist nur an wenigen Stellen zu beobachten, nämlich im Königin-Maud-Land, an den Randgebirgen der westlichen Westantarktis und naturgemäß im Graham-Land. An allen übrigen Stellen findet das Inlandeis die Möglichkeit, parallel zu den vorhandenen Bergketten gegen die Küsten hin abzuströmen, oder aber es sind überhaupt keine Bergdurchragungen vorhanden. Über die Strömungstendenzen im einzelnen bereits Aussagen zu machen, dürfte hingegen noch verfrüht sein, da über die Tiefenlage des Felsenuntergrundes noch viel zu wenig bekannt ist. Es ist durchaus möglich, daß unter dem Eise randliche subglaziale Gebirge vorhanden sind, an anderen Stellen wiederum fehlen, so daß Staubwirkungen, Düsenwirkungen und andere Einflüsse durchaus wahrscheinlich sind. Die Eisströme, Randgletscher, Spaltengebiete und andere Anzeichen von Störungen im normalen Eisabfluß, die randlich überall feststellbar sind, deuten auf ein oberflächennahes sehr unruhiges subglaziales Relief hin. Bestätigt wird diese Annahme durch die Ausformung der Durchragungen, soweit sie gebirgsbildend in Erscheinung treten.

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Limnological Investigations at Centrum Sø, Northeast Greenland*

by Daniel B. Krinsley, Washington **)

Abstract. The hydrography of Centrum Sø (lake), Northeast Greenland indicates that the valley now occupied by the lake was glaciated by an ice stream which moved from west to east. At present, the predominantly northwesterly winds during the winter deposit the thickest accumulations of snow along the longitudinal, south, and east-central porhons of the frozen lake, consequently, the thickest ice occurs adjacent to the northwest shore. During the thaw, 75 percent of the lake ice melted from the top down and 25 percent melted from the bottom up. When the lake is ice covered, horizontal and vertical differences in water temperature are greater prior to the removal of the insulating snow cover and diminish during the thaw period. These temperature differences, as much as 1.1° C. horizontally and 3.5° C. vertically, may be the result of convection currents generated by heat from ground water or bottom sediments, and warmer density currents from meltwater streams.

Zusammenfassung: Limnologische Untersuchungen am Centrum Sø, Nordost-Grönland. Die Hydrographie des Centrum Sø in Nordost-Grönland zeigt, daß das Tal, das jetzt von dem See bedeckt wird, vereist war von einem Gletscherstrom, der sich von Westen nach Osten bewegte. Gegenwärtig setzen die im Winter vorherrschenden nordwestlichen Winde die dicksten Anhäufungen von Schnee der Länge nach an den südlichen und mittleren östlichen Teilen des gefrorenen Sees ab. Entsprechend findet sich das dickste Eis entlang der Nordwestküste. Beim Auftauen schmelzen 75 % des See-Eises von oben und 25 % vom Boden. Wenn der See eisbedeckt ist, sind die horizontalen und vertikalen Temperaturdifferenzen vor der Entfernung der isolierenden Schneedecke größer und verringern sich während der Tauperiode. Diese Temperaturdifferenzen — etwa 1,1° C horizontal und 3,5° C vertikal — können durch Konvexionsströmungen bedingt sein, deren Wärme aus dem Grundwasser oder den Bodensedimenten sowie aus wärmeren Dichteströmungen des Schmelzwassers stammt.

Die limnologischen Untersuchungen, die in dieser Arbeit beschrieben werden, schließen hydrographische Untersuchungen, Schnee- und Eisdienst, Ablations- und thermometrische Messungen mit entsprechenden Beobachtungen der physikalischen Veränderungen des Sees während der Tauperiode ein.

Introduction

A scientific field party of the Ice-free Land Program of the Air Force Cambridge Research Laboratory landed at Centrum Sø (lake) in Northeast Greenland (fig. 1) on May 5, 1960. Studies in limnology, glacial

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geology, permafrost, and meteorology were conducted at the Centrum Sø area, lat. 80° 10′ N. and long. 22° W. Limnological investigations, which are described in this paper, included hydrographic, snow, and ice surveys, and ablation and thermometric measurements with correlated observations of the physical changes of the lake during the thaw.

Centrum Sø occupies the bottom of a northeast-southwest oriented glacial valley that has been cut 700 meters below an extensive plateau. The lake is 20 kilometers long and 4 kilometers wide near its midpoint (fig. 1); the surface is 98 meters above sea level. Principal tributaries, Saefaxi Elv and Graeselven *) (rivers), originate at the margin of the Greenland Ice Cap 40 kilometers west of the lake. Rivieradal is an important tributary valley to the southeast near the midpoint of the lake. The outlet into Lower Saefaxi Elv, at the east end of the lake, is 34 kilometers from the sea.

The bedrock surrounding the western two-thirds of the lake is part of a thick series of banded dark limestones and lighter dolomitic beds of Ordovician and Silurian age (Centrum limestone). The beds dip gently towards the east, but are tightly folded locally. East of the Centrum limestone along a strike approximately north-south, older dolomitic rocks, mostly of pre-Cambrian age, have been overthrust upon the Silurian limestones (Fränkl, E., 1954).

Glacias and glaciolacustrine deposits of variable thickness mantle the lower slopes and the high plateau above the lake. Recessional moraines on the plateau are convex downvalley and, along with associated marginal channels which have been cut in the steep valley slopes, have been traced westward to the margin of the Greenland Ice Cap (Krinsley, D. B., 1961). Well-preserved lake terraces, as much as 80 meters above the present lake surface, overlie coarse morainal materials and are associated with extensive lacustrine deposits of fine sandy red silt and coarser icerafted materials at the outlet of the lake. Random, shallow corings along the lake bottom consisted uniformly of fine red silt.

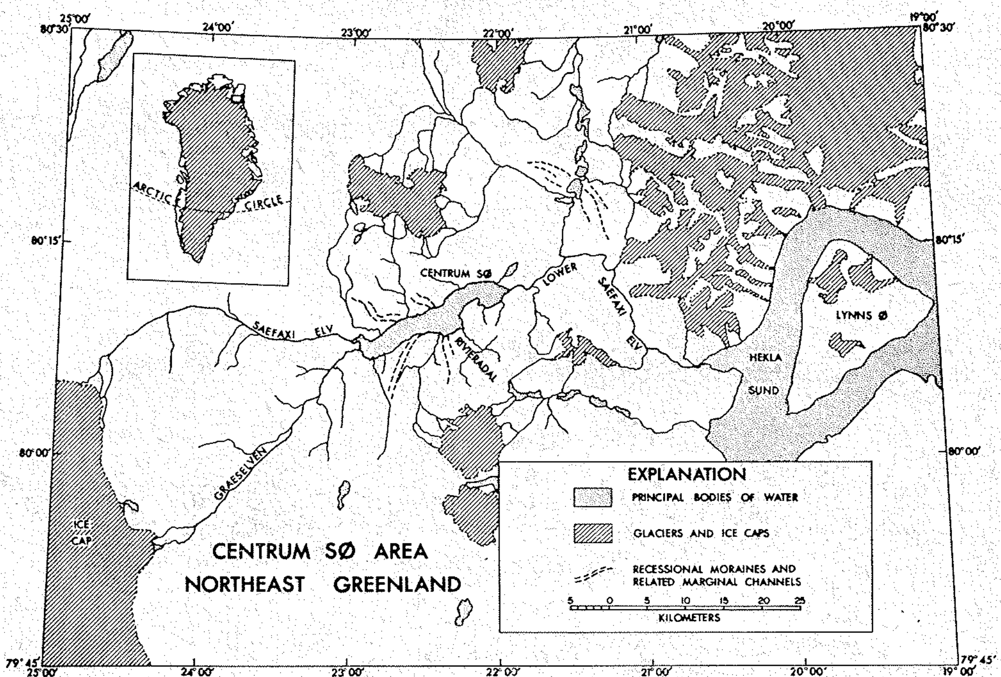

Figure 1

*) Provisional name

Centrum Sø freezes over in late September and breaks up in June; it is generally ice free in late July. There are no meteorological records for the winter months, and the nearest weather station at Nord, 205 kilometers northeast, has a considerably wetter climate so that extrapolation is not reliable. Meteorological data collected during the field season of 1960, together with the reports of previous visitors, suggest that the Centrum Sø area is an arctic desert with a total annual precipitation of 10 to 15 centimeters. Mean daily air temperatures ranged from —20.0° C. to 5.0° C. in May; —6° C. to 13.0° C. in June; and from 12.0° C. to 14.0° C. in July. The principal wind direction was from the west in May and June and from the southwest in July. Mean wind speed was about 13 kilometers per hour during the period May through July. On June 9, a wind storm from the north had gusts as much as 67 kilometers per hour.

Hydrographic survey

Transportation for the hydrographic survey was provided by a "Weasel" which was also used as a platform for the gasoline powered "Jiffy" ice drill equipped with a 2.44-meter, 10-centimeter diameter ice bit. Eighty soundings were made through the ice with a weighted, calibrated steel cable in order to obtain data concerning the hydrography of the lake. The valley occupied by the lake has a glaciated U-shaped profile as shown on the Hydrographic Map of Centrum Sø (fig. 2). The deepest part (78 to 79.50 meters) is a trough in the western half of the lake parallel to its longitudinal section; its bottom is extremely flat with a local relief of less than 1 meter. A broad delta currently being formed by the coalescence of deltaic deposits from Saefaxi Elv and Graeselven adjoins the deep trough. East of the trough, the lake bottom rises gently toward the outlet which does not exceed 6 meters in depth.

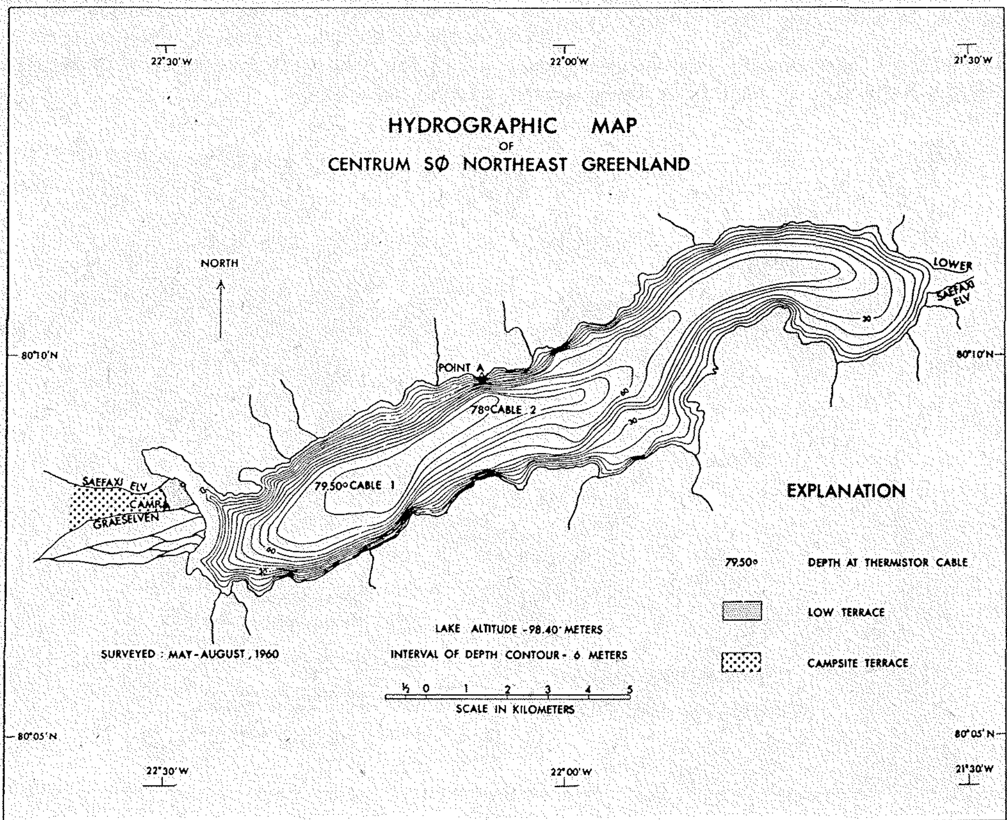

Figure 2

The hydrography suggests that the lake basin was glaciated by an ice stream which deepened the lake to within at least 20 meters of current sea level. The presence of the deepest portion in the western half of the lake suggests that this area was the last to be occupied by ice and that the glacier moved from west to east. This supposition is corroborated by the occurrence of paired marginal channels, convex toward the outlet, on either side of the lake shore (fig. 1). Moraines that may have occupied the basin were either destroyed by floods or buried by subsequent sedimentation.

Snow and ice surveys

The snow accumulation on the ice surface of Centrum Sø was greatest near the south and east shore of the lake (fig. 3.) because of the predominantly northwesterly wind during the winter. Snow cover adjacent and parallel to the north shore was 7.5 to 15 centimeters thick. Along the longitudinal section of the lake, the snow was 35.5 to 58 centimeters thick with the thickest area over the eastern third of the lake. Adjacent and parallel to the south shore, the snow was generally 51 centimeters thick with thinner areas (20 to 25 centimeters thick) over the eastern third of the lake. The more symetrical snow cover over the eastern third of the lake may be the result of eddy currents forming over the central third of the lake and then moving northeastward along the south shore. This possible mechanism is suggested by the form of the snow cover over the midsection of the lake which consists of composite snow lobes whose normal axes are oriented progressively counterclockwise to the northeast as the lobes are observed from north to south. Individual centers of accumulation particularly over the easternmost portion of the lake are controlled by the effect of the adjacent topography on the wind. It was difficult to measure the de-

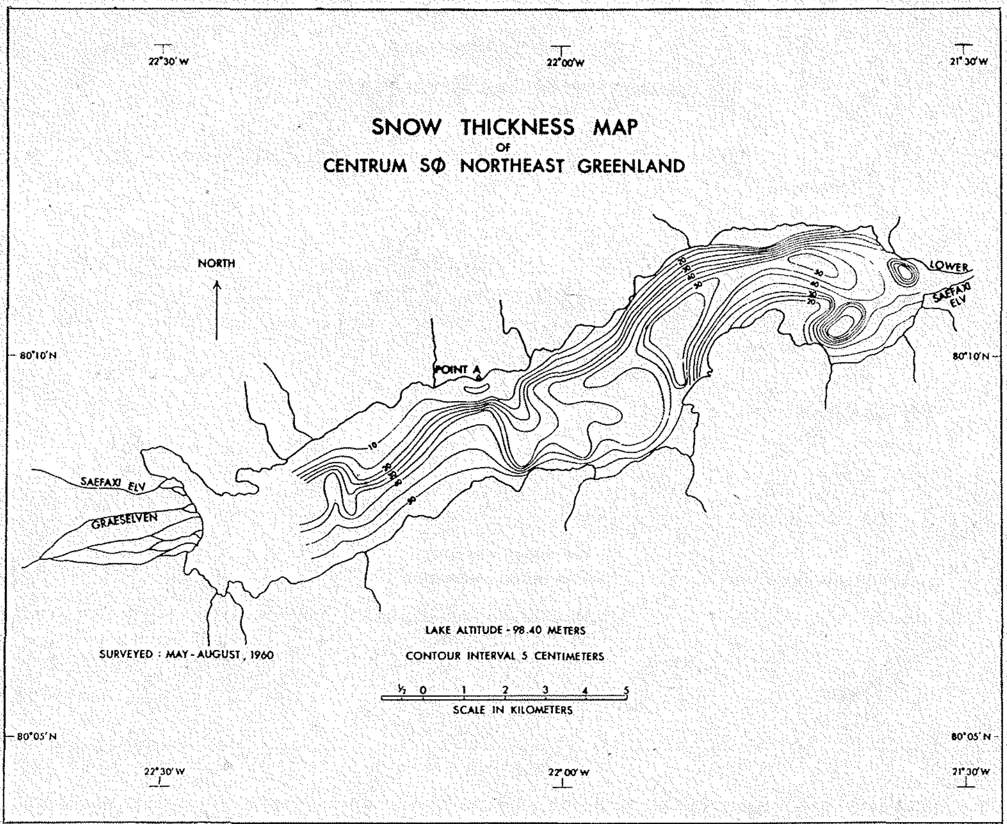

Figure 3

terioration rate of the snow cover because of the interference of stream overflows and ponding. During the last week in May, the snow cover thinned 10 centimeters adjacent tho the north shore and 18 centimeters in the thickest areas near the east end of the lake. The high air temperatures during the period June 1 through 15 reduced the snow cover to slush and water.

The Ice Thickness Map (fig. 4) is meaningful only after it is compared with the Snow Thickness Map (fig. 3). There is, as expected, almost perfect inverse relationship between the snow and ice thickness. Exceptions are limited and are principally at the east end of the lake where proximity to the outlet and its continually moving water have altered slightly the snow-ice thickness relationship. Deterioration of the ice proceeded most rapidly adjacent to the north shore where moating action *) was most intensive and the snow cover thinnest (fig. 3). The ice near the center of the lake, farthest from the peripheral moats and protected by a thick snow cover, thinned more slowly.

Ablation

On May 24, five ablation stations were established at 15, 30, 75, 150 and 1273 meters from the north shore of Centrum Sø along a line normal to the shore which intercepted thermistor cable 1 at the 1273-meter station (fig. 2). At each station a 10-centimeter diameter hole was drilled through the ice, and three translucent white plastic ablation disks, evenly spaced and suspended centrally by a white wire, were lowered into the hole and allowed to freeze in place. The ablation disks were marked

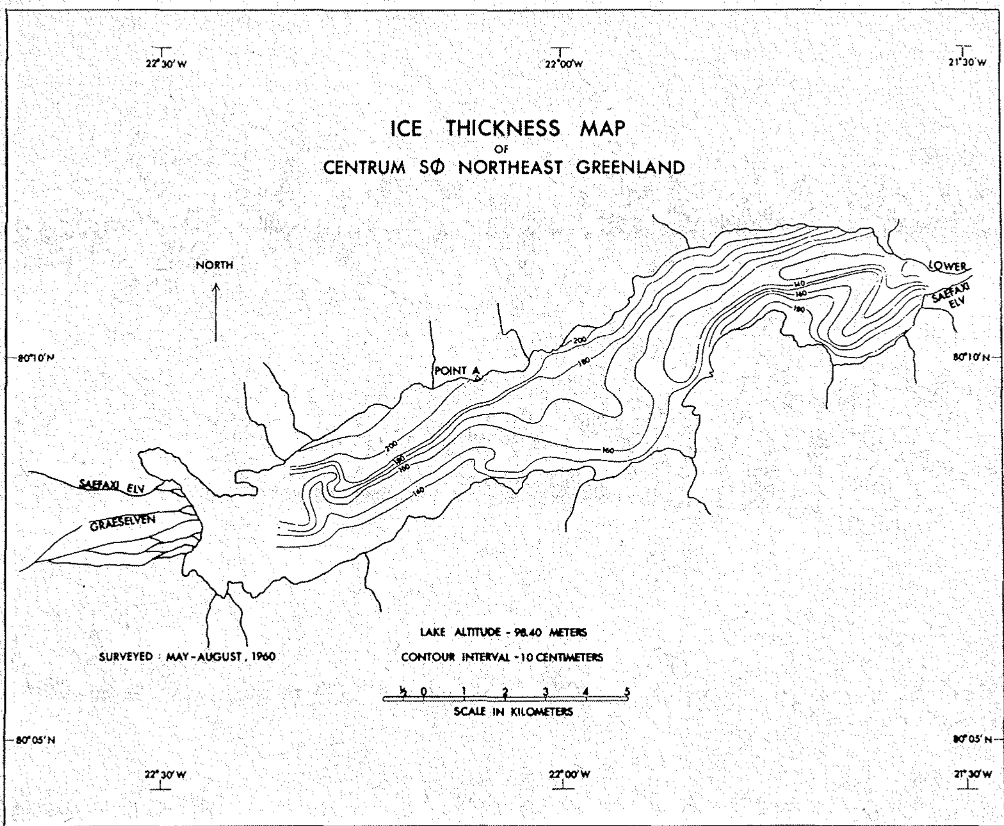

Figure 4

*) A moat is initially a depression in the ice surface formed by meltwater adjacent to the shore. Subsequently, the meltwater widens and deepens the moat (moating action) until the shore-fast ice is melted and the main body of the ice becomes free floating.

with reference to their position from the May 24 upper ice surface which was used as the ablation datum plane.

Measurements were made by drilling a hole adjacent to the ablation disks, recording the ice thickness, and then referring the new ice thickness to the exposed ablation disk.

At the 15-meter station (fig. 5), where the ice had been 198 centimeters thick on the day of installation, no ice remained by July 1. At the 30-meter station, where the ice had been 197 centimeters thick, 90 centimeters melted from the top and 54 centimeters from the bottom by July 20, immediately prior to the disappearance of all lake ice on July 26. At the 75-and 150-meter stations, where the ice had been approximately 194 centimeters thick, 88 centimeters melted from the top and 25 centimeters from the bottom by July 20.

At the 1273-meter station, which had had 173 centimeters of ice, 82 centimeters melted from the top and 15 centimeters from the bottom by July 20. This station on May 24 had 20 centimeters more snow than the landward stations. On June 14 as a result of the thicker insulation only 5 centimeters of ice had melted from the top surface while 10 centimeters of ice had melted from the top surface of the landward stations. After this date, the melting rate of the top surface was similar at all stations. The lower rate of melting at the bottom of the ice at the 1273-meter station was due to its greater distance from the peripheral moats.

These data indicate that during the period of thaw (May 24 to July 20) approximately 75 percent of the lake ice melted from the top down and 25 percent melted from the bottom up. There was more bottom melting at the moat and less bottom melting near the center of the lake. Barnes and Hobbie (1960, p. B392) reported that at

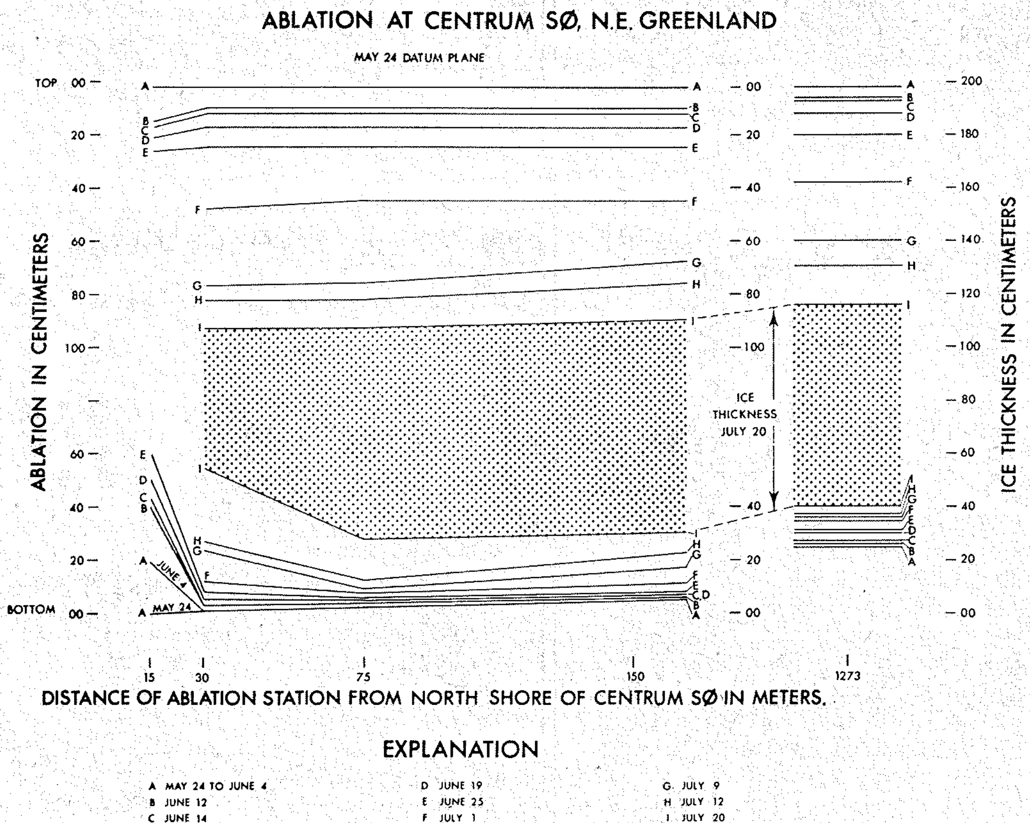

Figure 5

Lake Peters, Alaska, "not more than a few centimeters melted from the bottom of the (lake) ice sheet during the entire melting season." Hobbie (1960 p. 32), discussing ablation at Lake Peters, considered the effect of warm water (above 4 °C.) spreading under the ice on top of the denser lake water, but drew no conclusions concerning the relative amounts of top and bottom melting. The reader may assume from Hobbies' discussion that more than "a few centimeters melted from the bottom of the ice sheet" during the thaw period.

Thermal regime during the thaw

On May 15 and May 24, prior to the thaw, thermistor cables were placed in Centrum Sø. The two cables, supported by floats resting on the ice surface, extended through 30 centimeters of snow, 2 meters of ice, and approximately 78 meters of water to the fine sediments on the lake bottom. The suspended cables were located near each end of the trough-shaped deep in the western half of the lake (fig. 2). The thermistors in each cable were at approximately 3,30, 60, and 78 meters below the ice surface. They were accurate to 0.1° C. and were icepointed both prior and subsequent to their field use. Readings were made at intervals of from one day to three weeks and, during a 24-hour period beginning at noon May 29, cable 2 thermistors were read hourly.

Radiation fogs, rising from meltwater ponds, were observed in Saefaxi Elv during May 18 to 20, and at noon on May 20 an overflow from Saefaxi Elv spread out over a half kilometer square area adjacent to the river mouth. This overflow, resulting from increased meltwater because of higher air temperatures, initiated a general melt of the subjacent snow cover. By May 28 the overflow had spread 1.6 kilometers northeastward. A large pond of water occupied the mouth of Saefaxi Elv, and the following day isolated ponds developed on the lake ice and a moat, 20 centimeters deep and 6 meters wide, spread along the north shore and extended eastward to Point A (fig. 2). Isolated moats extended further northeast toward the outlet. The ice surface beneath the snow was wet. On May 30, as the result of a 13 °C. air temperature, the snow in the vicinity of Point A showed marked deterioration and 2.5 to 5 centimeters of water covered the ice surface. The zone of moating along the north shore widened southward across the lake and spread northeastward (by amalgamation with existing isolated moats) toward the outlet. No moating occurred along the south shore.

On May 31 the zone of moating extended southward to the vicinity of cable 2 where isolated ponds of water were 10 to 12.5 centimeters deep. Westward toward the mouths of the principal rivers, the water covering the ice was 15 to 20 centimeters deep where it was partly impounded by slush. The pond of open water at the mouth of Saefaxi Elv was considerably expanded and ice in the vicinity was covered by slush or as much as 25 to 30 centimeters of water and slush.

During May 28 to 30, the snow overlying and adjacent to the frozen Graeselven started to deteriorate and rills developed along the north bank. The meltwater ran beneath the snow cover, and isolated ponds developed near the mouth. On May 30, at approximately 5 p. m. local time, the snow had become sufficiently saturated so that water from upvalley spilled over the pond walls of slush and ice. Gradually the running water spread from pond to pond until a channel was eroded to the lake. The channel enlarged rapidly as meltwater from the surrounding slopes poured onto the frozen stream surface. The temperature on May 31 was 14° C. at noon. At 4 p. m., the channel of running water was 18 to 24 meters wide and 37.5 to 40 centimeters deep over the frozen stream surface. A zone of slush occupied each side of the channel.

On May 31, the lake water temperatures, which had been stable for several days prior to that date, rose 0.1° C. at the 3-meter thermistor of cable 1 and decreased 0.1° C. at the 60- and 62-meter thermistors of cable (fig. 6).

During the period from May 31 through June 6, Saefaxi Elv and Graeselven eroded channels through the stream ice, and a large volume of warmer water (3.8 ° to 8.0 ° C.) poured into the adjacent moats and under the lake ice which had broken away from

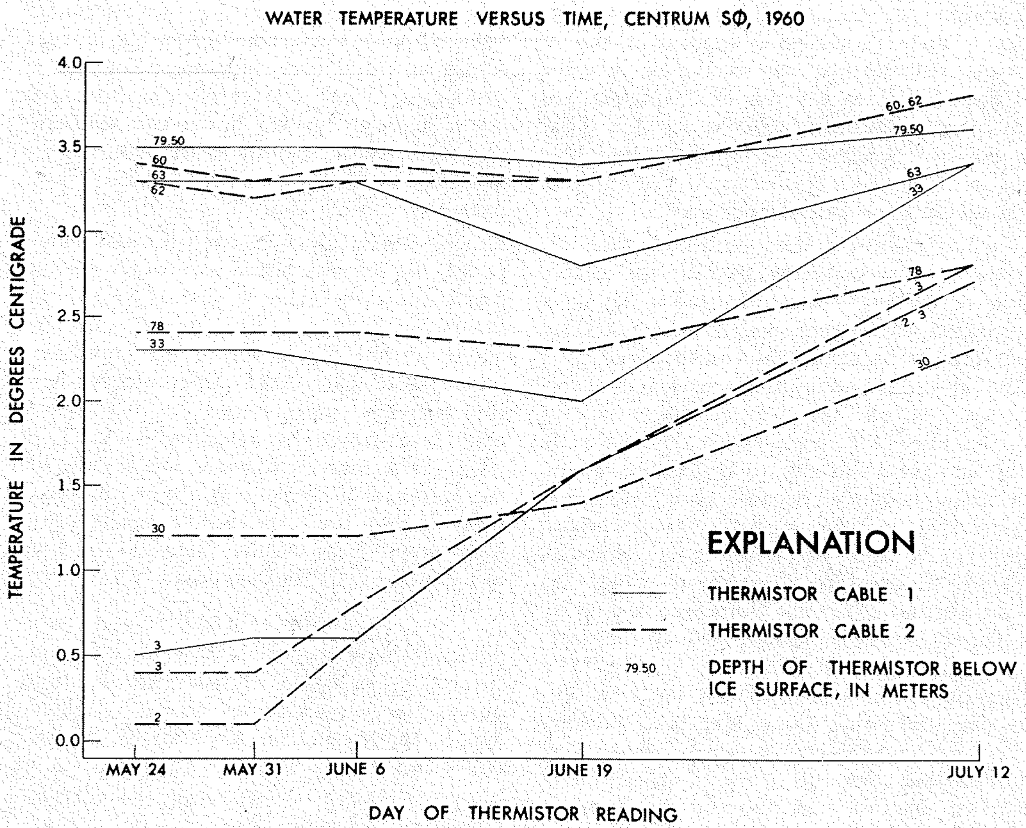

Figure 6

the shore bottom. The water which had accumulated on the surface of the lake ice drained into the rapidly widening moats. The firm lake ice surface deteriorated rapidly after May 31 and became candled by June 6 to a depth of 35.5 centimeters. On June 6, the cable 1 thermistor at 33 meters indicated a decrease of 0.1° C. in the water temperature. The cable 2 thermistors at 2, 3, 60, and 62 meters indicated a rise of 0.5°, 0.4°, 0.1°, and 0.1° C. respectively.

A staff gauge for measuring the lake level was installed on June 7. Three days later, the lake had risen 30 centimeters and by late June the level of the lake was temporarily stabilized. The lake ice deteriorated rapidly by candling. On June 19 the cable 1 thermistor at 3 meters indicated a 1.0°C. rise in water temperature although all other thermistors in the cable recorded a decrease in water temperature (fig. 6). At cable 2 the three upper thermistors recorded a rise of 1.0°, 0.8°, and 0.2° C. As at cable 1, the lower thermistors of cable 2 indicated a decrease in water temperatures.

During the first week in July, the lake rose 1 meter, and a 5-meter wide crack in the lake ice developed in the vicinity of cable 2. The ice in this area had thinned from 183 to 120 centimeters. The moat was continous around the lake but it was bridged locally by ice which shifted with changing wind directions. The lake rose a total of 2.5 meters by July 9, subsequent to the installation of the staff gauge on June 7; and 75 centimeters of water flooded the low terrace adjacent to the campsite (fig. 2). The lake receded from this maximum level the next day. The moat was now from 7.5 to 15 meters wide around the lake, and several cracks formed in the ice near the center of the lake.

On July 12, the thermistors were read for the last time and were removed because of possible ice damage. All thermistors in cables 1 and 2 recorded a significant rise in water temperature; the maximum in cable 1 was 1.4° C at a depth of 33 meters and in cable 2 the maximum rise was 1.2° C. at a depth of 3 meters. During the period July 10 to 25, melting was so rapid that by July 26 all lake ice had disappeared.

The temperature data indicates that although water temperatures near the surface and on the lake bottom changed in the same direction, there were significant temperature differences between cables in the same horizon at the same time. Temperature differences between the 3-meter thermistors of both cables (1.2 meters below the bottom of the ice) were not due to differences in the local environment because both instrument platforms were covered by white canvas, and snow and ice cover were identical. Small temperature fluctuations along the lake bottom could not have been caused by different radiative properties of the sediments as suggested by Brewer (1958, p. 281), because of the uniformity of the fine sediments (red silt) along the lake bottom. Temperature changes between cables were in the same direction in the 60- to 63-meter horizon but were in opposite directions in the 30- to 33-meter horizon during the period June 6 trough June 19 (fig. 6).

When the lake is ice covered, horizontal and vertical water temperature differences are greater prior to the removal of the insulating snow cover and diminish during the thaw period. During a critical 24-hour period, on the threshold of the lake thaw, when the air temperature fluctuated 5.0° C. and the snow cover was reduced to slush, there was not more than a .03° C. (4 ohms resistance) fluctuation in water temperature and this occured at a depth of 63 meters.

Solar radiation, even differentially applied, as in the case of sunlight and shadow alternately produced by a low arctic sun on topographic obstacles, cannot affect water temperatures prior to the removal of the snow cover. The principal tributaries of Centrum Sø freeze to the bottom so that they cannot add heat to the lake until they break up (June 1).

Prior to the breakup of the streams, heat may enter the lake from the flow of ground water beneath the streams, from sublimnol springs, and from the bottom sediments. These potential heat sources are capable of generating local convective systems that could account for the horizontal temperature differences, as well as the temperature anomaly which occurs at the 78-meter thermistor of cable 2 (fig. 6).

During the breakup of the principal tributaries, the warmer but denser water (3.5 to 4.0° C.) reaches cable 1 first (fig. 2) and, displacing lighter, colder water, may account for the persistence of the horizontal temperature differences along the lake bottom between cables 1 and 2. This mechanism is discussed by Hutchinson (1957, p. 476), "The most reasonable explanation of the observed phenomena (bathylimnetic heating) is that they are due to density currents running down the slope of the lake basin towards its deepest point."

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