CONTRIBUTIONS TO THE GLACIOLOGY OF THE SEWARD ICE FIELD, CANADA, AND THE MALASPINA GLACIER, ALASKA

Thesis

by

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Frontispiece. Outlet from Seward Ice Field where Seward Glacier drains to the great Malaspina Glacier. Photograph by Professor Robert P. Sharp.

Mount Logan (19,850 feet), second highest peak in North America. Photograph by Professor Robert P. Sharp.

ABSTRACT

Certain phenomena of the Seward Ice Field and the Malaspina Glacier as observed in the summer of 1948 are interpreted in the light of glaciologic literature.

Inferences on glacier regimen are drawn from accumulation and ablation measurements. The efficacy of the ablation factors is discussed and analogies are deduced by comparing ablation and meteorological data with those collected by Scandinavian glaciologists on the Vatnajökull, Iceland. The meteorological factors play an overwhelmingly important part in ablation on the Malaspina Glacier and probably retain their advantage over radiation at a higher elevation on the Seward Ice Field.

Distinctions are made between indirect, internal, net and gross ablation. The formation of a glacier water table and the incidence and dissipation of the winter cold wave on the Seward are discussed.

Two contrasting types of differential melt-depressions were noted on the Seward, inclined underwater ice wells and vertical wells not underwater. Previous theories of ice-well formation are critically analysed. The deepening of the ice wells beyond the depth at which the depression is shaded from the sun is believed to be produced by diffuse radiation, with reflected direct radiation playing a minor role. Experiments with artificial ice blocks attest to the

importance of vertical gravity settling of debris in ice wells and fail to account for the inclination of the underwater ice wells.

Melt-water movement studies were undertaken during a period in July and August. The quantities of melt-water percolating through the firn were measured at various depths and are compared to the ablation record, the meteorological record, and to the time of day in this paper. There is little correlation between the daily melt-water record and the daily sunshine and ablation records. Air temperature is the most significant index of melt-water production. However, the average maximum temperature was reached between 11 and 12 A.M., and the average hourly maximum melt-water collected was recorded between 5 and 6 P.M. The fact that the upper firn layers produced less water than deeper firn layers is evidently due to the greater capillary flow and less concentration of melt-water in the upper firn.

INTRODUCTION

Introductory Statement

During the past 50 years the science of glaciology has advanced, not only as a result of polar expeditions, but through the study of lower latitude glaciers. Recognizing the scientific value of Alaskan glaciologic investigations, the Arctic Institute of North America commenced a five-year expeditional program the summer of 1948 on the unexplored Seward Ice Field and the Malaspina Glacier.

Purpose and Scope of the Work

The program of work was exceedingly comprehensive, but the first summer's results were only preliminary. This thesis summarizes the work done during the first summer's investigations with the exception of two rudimentary phases, glacier movement studies and bedrock geology. It is based partly on inexhaustive observations and partly on considerations of ice fields and glaciers elsewhere as described in the literature. Although the inadequacy of data is felt, it is hoped that the combined study of the observed data and of the modern concepts and information on glacier phenomena elsewhere will be illuminating and will contribute to further studies.

Location and Size of the Area

The Seward Ice Field is a broad accumulation basin of at least 600 square miles located for the most part in the Yukon territory of Canada at N. Latitude 60°23' and W. Longitude 139°53'. It appears flat-lying from the air, but ranges in elevation from approximately 5500 feet to 6100 feet. A rugged subglacial topography is envisaged from the many projecting nunataks. The imposing ice-clad mountains of the St. Elias Range completely surround the ice field except for a col to the west and a drainage-way to the south. The Seward Ice Field drains southward to the piedmont Malaspina Glacier of Alaska by way of the Seward Glacier which loses almost 5000 feet elevation in its 15 mile descent. Consequently, the lower sector of the Seward Glacier is so full of wide and deep crevasses as to be practically impassable.

It is in the Seward lobe that the Malaspina Glacier extends farthest from the mountains, reaching the beach at Sikagi Bluffs, but not calving icebergs. The surface of the Malaspina is a vast expanse of clean ice with areas of ablation moraine around the periphery and with sinuous medial moraines between glacier lobes.

Personnel

Nineteen men participated in the expedition activities which were organized and ably led by Walter A. Wood, Director of the New York office of the Arctic Institute. Professor Robert P. Sharp of the California Institute of Technology headed the glaciologic group composed of California Institute of Technology graduate students George P. Rigsby, Bernard O. Steenson and the author, and Maynard M. Miller of Columbia University. John H. Ross of Pennsylvania University was the expedition meteorologist. Other members of the expedition included representatives of the Canadian Research Council, the Harvard Mountaineering Club, and officials of the Arctic Institute.

Summer Itinerary

Six days were spent on the Malaspina periphery near Sitkagi Bluffs from July 3 to July 9. On July 10 the glaciologic party was flown to the Seward Ice Field where studies were made until August 29. Five camps were established on the Seward Ice Field during the summer as a basis for field work. The main base station was located on a nunatak and will be referred to hereafter as the Nunatak Station. Two and a half miles west near the landing area used by the ski-plane was the Airstrip Station. Two other stations, Stations 3, and 4, were situated near the northern bedrock rim of the ice field. The fifth camp was a mile northeast of the Nunatak Station, but is not referred to in this paper.

Meteorological Observations

Daily meteorological observations were necessary to supplement the glaciologic work. U.S. Weather Bureau equipment consisting of thermometers, a sling psychrometer, a barometer, and an anemometer were employed at the Nunatak Station (elevation 6020+ feet) from July 4 to August 29. Each night the weather data was radioed to the Yakutat Weather Station, approximately 60 miles distant. At the Airstrip Station (elevation 5720+ feet) maximum and minimum temperatures were recorded from July 4 to August 29, and a daytime hourly temperature record was kept from July 12 to August 3.

Acknowledgments

I am particularly indebted to Professor Robert P. Sharp for the opportunity to join the expedition as his assistant. His expert advice in the field and in the writing of the thesis was most helpful. The high morale of expedition members reflected the inspiring leadership of Walter A. Wood. His professional handling of the logistics of the operation expedited the field work of

the glaciologic group and deserves special mention. Maynard M. Miller and George P. Rigsby contributed greatly to all phases of the field work and were excellent field partners. To Mauri King, Francis P. Magoun III, Robert S. McCarter, Allen Bruce Robertson, John H. Ross, and Bernard O. Steenson I am grateful for their cooperation and companionship.

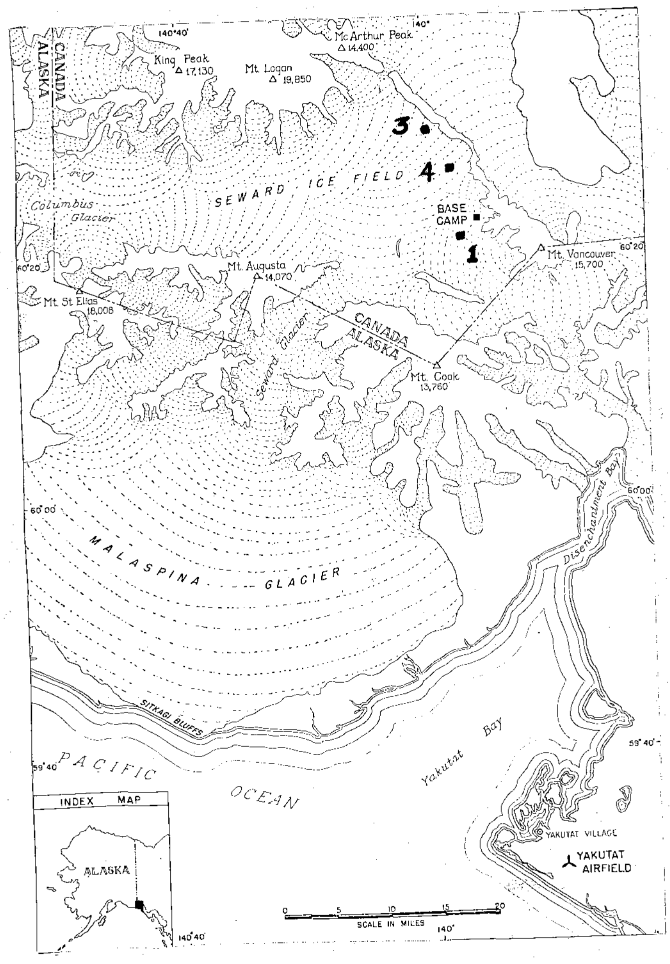


FIGURE 1a.-Index Map
Base camp = Nunatak Station
Station 1 = Airstrip Station
Stations 3 and 4 = Stations 3 and 4.

GLACIER REGIMEN

The two factors which are the most important in the life of a glacier and comprise its regimen are accumulation and ablation. Seligman includes wind erosion and Ahlmann includes calving and wind corrasion as factors in ablation in addition to melting and evaporation. Only the latter two processes are recognized as ablation by most American glaciologists and this usuage will be followed here. Rendu (1841, pp. 43-44) and Agassiz (1840, p. 22) were the first to divide glaciers into two parts, the _glaciers' reservoirs_, or _mers de glace_ (English accumulation area) and the _glaciers' d' ecoulement_ or _glaciers' proprement dits_ (English ablation area). The boundary where accumulation equals ablation Agassiz (1862, p.45) named the _neve line_ (or _firn line_ in German).

By direct measurement of annual accumulation and ablation in the accumulation area and the ablation area it is possible to determine the glacier's regimen. The greater the net accumulation, morphologic factors being equal, the more active is a glacier. (Ahlmann, 1933, pp. 290-291). The Seward Ice Field is of such magnitude that it reacts much slower than a small glacier to changes in its regimen. Although one summer's observations on the Seward Ice Field were inadequate to deduce regimen results, the observed data are herein recorded. These data are discussed in the light of modern concepts and information on glaciologic phenomena, and inferences are drawn.

Accumulation

In this paper accumulation refers not to the solid precipitation which has fallen or has been deposited in a particular spot, but to the precipitation which has accumulated in that spot. Although there was little wind on the Seward during the summer, wind drifting may be a prominent factor in the winter.

Accumulation includes not only precipitation in the form of snow, but rime, hoar frost, and rauhfrost, which is the intermediate state. (Seligman, 1936, p. 49). The importance of arien deposits to the alimentation of the Seward Ice Field is unknown; only one occurrence was noted during the summer. Rime was deposited the night of July 15th during freezing temperatures when a fog blanketed the ice field.

Annual accumulation is usually expressed in terms of its water equivalent which is the product of the thickness and density. Total annual accumulation can be determined by digging or coring in early spring down to the previous summer's ablation level or to the surface of the preceding year's snow and by measuring the vertical section to gain the accumulative water equivalent. This calculated amount of solid precipitation is usually approximate, because of the ablation intervals following times of precipitation and the wide range of snow densities averaged. Therefore measurements generally involve a net accumulation over ablation; reduced accumulation thus has the same effect as increased ablation. If conspicuous dirty horizons are present and can be identified as annual dirt bands, the annual layers will yield the net accumulation. By staining the surface artificially with a substance insoluble in water, the net accumulation can be measured in a succeeding year.

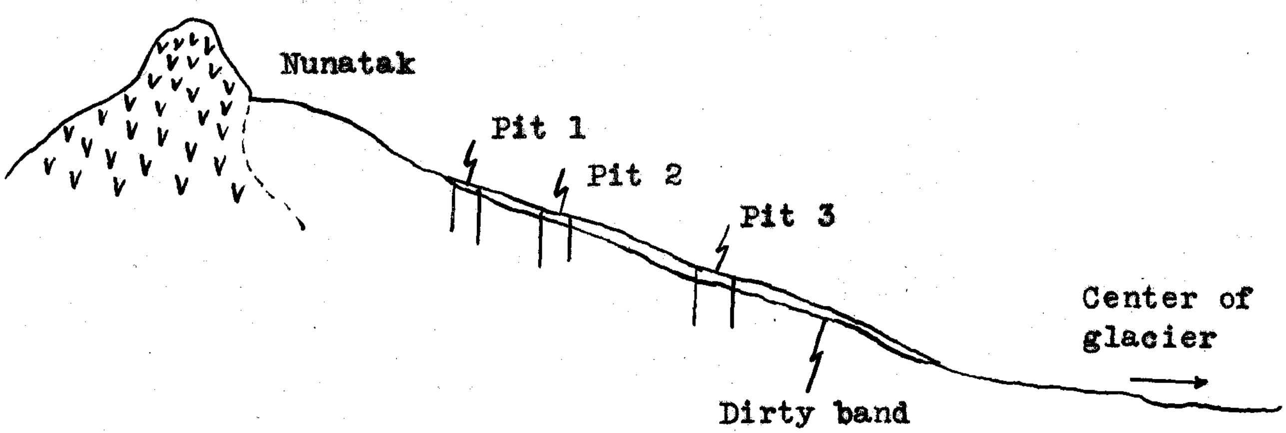
Eight pits were dug in the firn of the Seward Ice Field and attempts made to study net accumulation for the year 1946-47. Near the Airstrip Station where there is no marked relief, pits revealed dirty horizons 85 cm. apart with densities ranging from 0.47 in the dirty horizons to 0.59 just above the lower dirty band. If these two prominent dirty horizons are annual dirty bands, the net accumulation for 1946-47 was 44-45 cm. of water. Towards the northern rim of the Ice Field at Station 3 another pit dug on a 1° 30' slope indicated a greater net accumulation for 1946-47 of 93.5-95.5 cm. The net accumulation at both stations for 1946-47 compares favorably with that for 1947-48; on August 23 when ablation seems to have come to an end for the season, the excess of accumulation over ablation for 1947-48 was 58.5-60 cm. at the Airstrip Station and 82-84 cm. at Station 3. Presumably a combination of more snow-drifting and less ablation accounted for this greater accumulation at Station 3. Unlike the Airstrip Station which is protected from northern winds by the higher mountains, the northern rim is relatively unprotected, and as a result cold northern winds were experienced there even during the summer.

Another pit dug on the top of a hill near the north rim (Station 4) revealed one dirty band almost at the surface and another 180 cm. below, or at a depth equal to the thickness of the 1946-47 annual layer at Station 3. If the topographic locality of Station 4 accounts for the lack of accumulation for 1947-48, it does not account for the large reduction in accumulation after 1946-47.

The accumulation data for the three stations are summarized on the following page.

Station	No. of Pits Dug	Depth of No. 1 Dirt Band Aug. 26	Thickness of Annual Layer	Range of Density	Average Used	Accumul. 1946-47 in Cm. Water	Est. Accum. 1947-48 in cm. Water
No. 1	3	113 cm.	85 cm.	.47-.59	.52-.53	44-45	58.5-60
No. 3	1	158 cm.	180 cm.	?	.52-.53	93.5-95.5	82-84
No. 4	1	0-2 cm.	180 cm.	?	.52-.53	93.5-95.5	0

Three pits were also dug in the small valley glacier near the Nunatak Station on a slope of 3-5°. Although a 10 foot depth was reached, only one dirty band 70 cm. below the surface was encountered. At the close of the summer this dirty horizon could be traced from the surface of the snow near the Nunatak down the slope towards the center of the small glacier, as shown in the sketch below.



Scale: 1 inch = 100-150 yards
Vertical scale exaggerated.

FIGURE 1.-Transverse profile near Nunatak Station.

Similar profiles of dirty bands were probably true of other slopes affected by the reflection and conduction of radiation from nearby bedrock. On such slopes there is no excess accumulation except on lee sides or other spots where drifting has occurred. As a working hypothesis it is suggested that the dirty band in the sketch on page 12 has been exposed surficially year after year as a result of the summer's ablation. Thus for the latter part of several summers as the dirty layer becomes thicker and absorbs more heat because of its darkening color, it melts downward by indirect ablation, and the dirty horizon becomes more pronounced after each summer.

The following facts support this hypothesis:

1. The dirty band is very prominent (up to 9 cm. in thickness) near the Nunatak, but it is much less so elsewhere where there is a surplus accumulation for 1947-48.

2. In pit No. 1 10 feet deep, no dirty band was encountered below the dirty horizon at 70-77 cm.

3. An ice band up to 11.5 cm. in thickness and lying 91.5 cm. below the dirty band could not in all probability have formed in two years.

4. Patches of last year's snow, where left, are very white compared with the surface

where the dirty band is exposed. Therefore the dirty horizon must be the result of several years of silt accumulation.

Before these preliminary figures for annual accumulation on the Seward Ice Field can be accepted as authentic, proof that the dirty bands uncovered at the Airstrip Station do not represent more than one ablation season is needed. These same figures are to be checked in 1949, and the dirty bands will be compared with the dirty surfaces stained with iron oxide and lead oxide at the end of the 1948 summer.

Surface Ablation Measurements

Surface ablation is measured by noting at recorded intervals the lowering of the snow or ice surface relative to a stationary vertical gauge, or to an index ice or dirt band in the walls of a pit. Measurement upward from an index band is less accurate because these bands thicken and thin in space and time. Consequently, gauges or stakes are preferred, and two intricate ablatographs have been introduced.[1,2]

Ablatographs are precision instruments, which not only reduce the human error in stake measurement, but permit accurate hourly determinations of ablation and the continuous recording of the lowering of the snow surface. Continuous packing of the snow adds a complicating factor, which is reduced if the supports of the ablatograph are driven deep enough into the firn, or if graduated stakes are read and reset daily. Inasmuch as simple graduated stakes were used to measure ablation in the preliminary investigations on the Seward-Malaspina in 1948, the advantages and the disadvantages of the method will be discussed to the exclusion of the ablatographic method.

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1. Ahlmann describes the ablatograph designed by Dr. O. Devik in the Geografiska Annaler, vol. 17, pp. 43-46 and vol. 24, pp. 3-6.
2. Rudolf Von Huene of the California Institute of Technology designed a new ablatograph which will be tested in Alaska in 1949.

The type of stake is important. Obviously, wooden stakes are better than metal ones, because the former are poorer conductors. The stakes should be white in order to reflect insolation. They should be light to avoid sinking in the firn by their own weight, yet sturdy enough to remain secure during the ablation interval. The depth of burial of the stakes depends in part upon the anticipated ablation rate and ablation interval.

Above the firn line, stakes can usually be driven into the firn; below the firn line an auger drill must prepare the hole in the ice. Stakes set in the firn should be reinserted in a new hole after every regular observation.

In summary the measurement of ablation with graduated stakes is subject to the following types of error:

I. Errors inherent in the ablation stake.

1. Sinking into the firn due to the weight of the stake.
2. Melting into the firn due to the heat absorption of the stake.
3. Melting of cuplike depressions around the stakes increases the error of measurement.

II. Errors resulting from local environmental factors.

1. There is greater ablation where more surface area is exposed.

a. At ice falls where the glacier is crevassed and separated by narrow ridges.

b. At runnels and other surface irregularities.

2. There is greater ablation near bedrock outcrops.

3. There is generally greater ablation on a slope than on a level.

III. Errors inherent in the firn properties.

1. Sinking of the stake due to the settling of the snow.

2. Irregular and unequal ablation rates due to the variable albedo of the snow surface.

   a. Dirty bands and pockets, and ice bands ablated to the surface.

IV. Human errors in measurement.

1. Projecting the level of the snow surface to the graduated stake upon reading and resetting.

2. Extending the intervals of measurement so that no record of the ablation of snow falling between observations is added to the gross ablation. The net ablation, or regimen balance, will not be affected, however.

Measurements of the Surface Ablation on the Seward-Malaspina

Only one ablation stake was set on the Malaspina periphery, because of failure of the star drill. This 9-foot 5-inch maple dowel was placed in a hole 8 feet 6 inches deep, 2 miles inland at the outer edge of debris-free ice on July 6. On July 8, 44 hours following the setting of dowel, the glacier surface had been lowered 6¾ inches, or at a rate of almost 3½ inches per day.

Ablation measurements on the Seward Ice Field began on July 12. Meter sticks were read and reset daily in the firn. The 24-hour ablation interval from 7 P.M. to 7 P.M. corresponded to the meteorological day. The arithmetical mean of three meter stick readings was used when it was discovered that snow surface irregularities could cause anomalous ablation measurements of one meter stick. It was necessary to project the level of the firn surface to the meter stick scale, because of the cuplike depressions that formed around the stick. This introduced an error ranging from a fraction of a millimeter to 2 millimeters, as estimated by Sharp.

Daily ablation measurements were made from July 12 to August 3 at the Airstrip Station, and were resumed at the Nunatak Station for the period August 5 to August 13. Stakes which served as gauges for ablation and as stations for determining glacier movement were placed in a semi-circle around the Nunatak Station on July 25. The average ablation for 2 of these stakes was 405mm. on August 23. A total ablation approximation of 675mm., or an approximate average of 16mm. a day, is arrived at for the period July 12 to August 23, the date ablation was impeded. Figure 2 shows a reconstructed section of the firn ablated from July 12 to August 3.

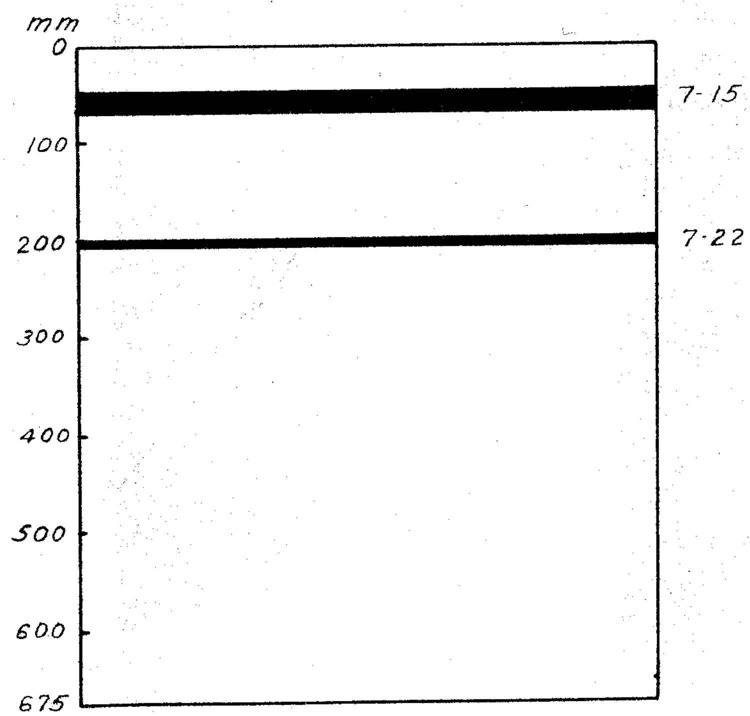

FIGURE 2.—Reconstructed section of firn ablated from July 12 to August 3. (Black bands are ice bands; dates are those when the ice bands were ablated.)

Computed water equivalents of ablation values are more accurate than computed water equivalents of accumulation values. No snow flakes in their original feathery hexagonal form remained on the Seward Ice Field at the time of our investigations. The ablated firn had a density of close to 0.50, as contrasted to the wide range of lower densities in newly fallen snow. Thus diurnal ablation figures should be halved to obtain their water values. However, the water equivalent of the total ablation figure will be less than half, for of the 675mm. ablated, at least 300mm. was newly fallen snow.

Rates of ablation, although dependent largely on the meteorological factors, are sometimes greatly affected by the varying density of the glacier surface. Disregarding the meteorological factors, the lower the density the more rapid is the ablation. Small feathery flakes of snow are naturally melted more easily than denser and rounder firn crystals. Daily ablation extremes, ranging from 0 to 145mm., resulted from melting following infrequent falls of snow on the Seward during July.

New snow not only melts rapidly; it settles rapidly. Therefore, measured ablation of new snow includes an unknown amount of settling between readings. If refreezing of melt-water is precluded in the interim of settling, and if densities of the snow before and after settling are known, the amount of settling can be calculated.

Inasmuch as the ablation measurements at the Nunatak Station were made on slopes at an altitude 300+ feet above the general ice field level, they are probably not as trustworthy as the measurements made at the lower flat-lying Airstrip Station. The ablation record at the Airstrip Station has the additional advantage of proximate hourly melt-water and meteorological records.

FIGURE 3.—The relation of ablation to the air temperature and the hours of sunshine for the period July 12 to August 3 at the Airstrip Station.

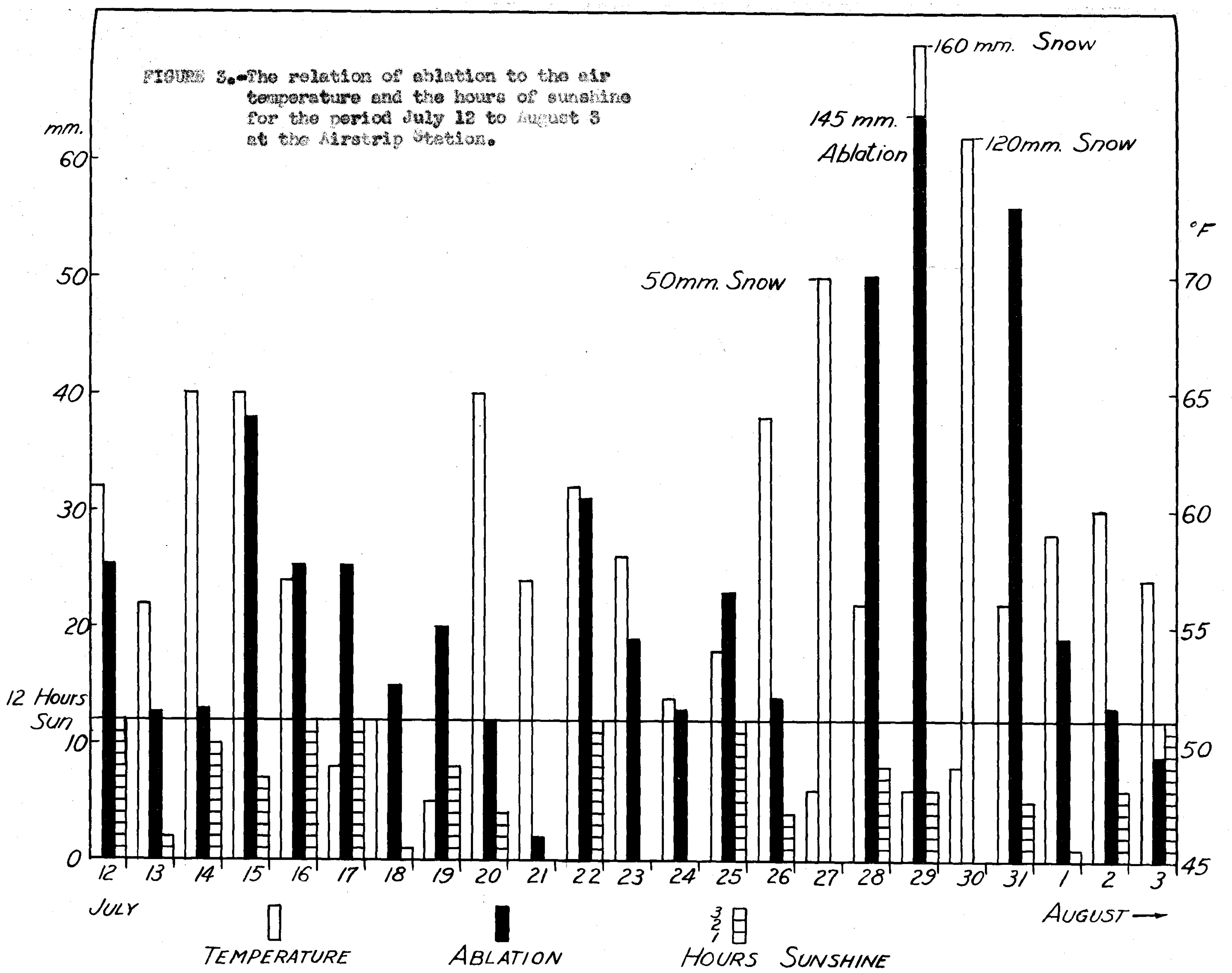

Figure 3 compares ablation with the temperature and sunshine record for July 12 to August 3 at the Airstrip Station. Maximum diurnal temperature values are substituted for mean diurnal temperature values because they render a more accurate correlation with ablation values. The meteorological record (Appendix A) shows that days having higher maximum temperatures also had lower minimum temperatures. This gave an abnormally low mean temperature for an unusually hot day when ablation was extreme. The use of maximum temperature has one particular disadvantage. In inclement weather the temperatures sometimes remained above freezing during the night, resulting in continued nocturnal ablation. In Figure 3 this happened to some extent on July 19, 23, 24, and 31.

Although air temperature is probably the most important factor influencing ablation, no one meteorological factor can be used to predict the ablation every day. For example, on July 28, 29, and 31 the melting of a newly fallen snow increased the recorded ablation.

The character of the firn surface may also complicate the ablation-meteorology correlation. If a silty horizon is exposed at the surface, ablation proceeds at a faster rate than usual. A newly exposed ice band has the same effect to a lesser extent. The large ablation figure of 38.1 mm. on July 15 may partly reflect the surface exposure of a one-inch-thick ice band.

Theoretically the firn line is the highest level at which the winter's snow cover on a glacier's surface is entirely ablated. Generally it is not a sharply marked boundary line, but a zone in which zones of snow-bare and snow-covered firn alternate. Such an area extended up the Seward into the ice field by the end of summer, so that the terms ablation and accumulation areas became inapplicable. This irregular retreat of the firn line seems to be true of the majority of St. Elias Range glaciers.[3] Not only are the areas near bedrock outcrops relieved of the past winter's snow, but areas removed from the influence of these outcrops are bared, and these coalesce as the summer progresses.

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3. Maynard M. Miller, oral communication, 1948

Ablation Factors

Ablation takes place by melting or evaporation, or by both of these processes. Melting results chiefly from the latent heat of condensation, heat convection-conduction, radiation, and warm rain. Evaporation takes place as sublimation, the latent heat of sublimation being equal to the sum of the latent heat of fusion and the latent heat of vaporization or 680 calories.

Evaporation versus Condensation

Air which is in contact with the snow has a temperature of 32°F., and a water vapor content corresponding to saturation at the given vapor pressure. If the air above the snow surface is warm and wet, the water vapor content increases rapidly with increasing distance from the surface (to a limit), and air which is saturated with vapor some distance from the surface becomes supersaturated when eddy-conducted towards the surface. Here the water vapor condenses and liberates heat. However, if the dew-point of the air above the snow surface is less than 32°F., the vapor content of this air will be less than at the snow surface, and evaporation instead of condensation will occur, thus cooling instead of heating the snow. Sverdrup (1935, p. 150) observed an interesting difference between the character of the firn surface depending on whether condensation or evaporation takes place. In the former case the surface becomes granular, but when evaporation takes place the surface attains a "leafy structure".

Evaporation and condensation are almost linear functions of wind velocity and temperature (Wilson, 1941, p. 186), but evaporation increases with decreasing humidity and condensation decreases. If the dew-point of the air is less than 32° F., and more heat than necessary for evaporation is supplied to the snow surface, melting will be concomitant with evaporation. Figure 4 (Light, 1941, p. 199) shows melting as a function of relative humidity and temperature for a unit wind velocity, but does not consider radiation effects. The boundary between evaporation and condensation is represented by a red line. It is noteworthy that any temperature below 32° F. gives an evaporation-loss. Thus evaporation becomes the sole component of ablation during sub-freezing weather neglecting radiation effects. Erickson (1942, p.30) implies that the process of evaporation cannot progress without melting. It is evident from the graph that air temperatures up to 51° F. are possible without the occurrence of melting if the air is sufficiently dry and radiation is

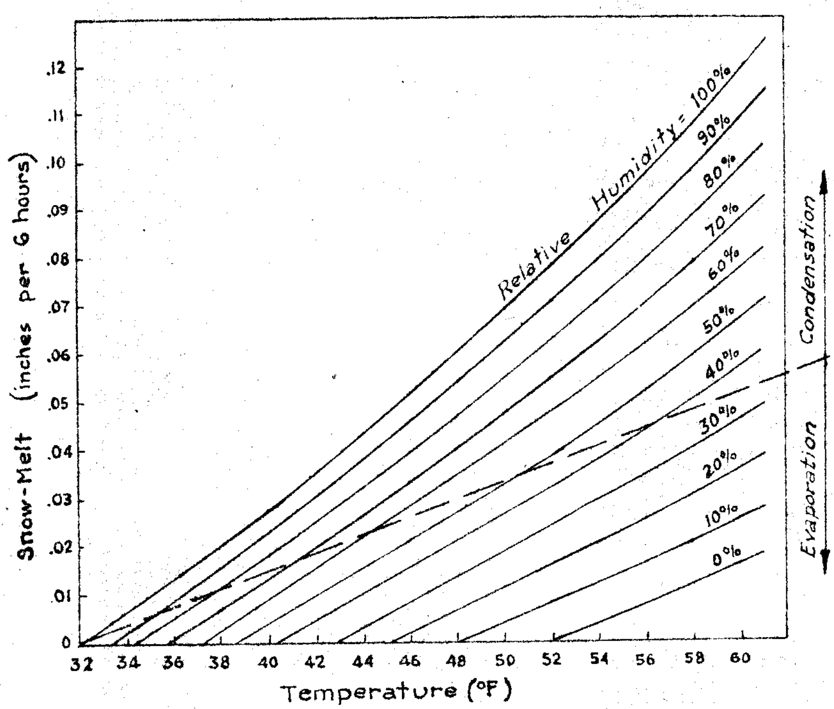

FIGURE 4.—Melting as a function of relative humidity and temperature for a unit wind velocity. (After Light)

insignificant. Light states that the graph neglects the elevation factor, but that for higher elevations evaporation becomes more important and still greater temperatures are possible without melting. However, referring to Figure 3 it can be concluded that there were few periods of relatively high temperatures on the Seward without profuse melting. Even at times of very low relative humidity the ablation rate increased instead of decreasing. (See Figure 5)

On account of the high elevation of the Ice Field and the large number of dew points below 32°F., it was suspected that evaporation might be of more importance here than in some other areas studied. (Sverdrup, 1937, p. 197). The well-known maritime climate of coastal Alaska suggests a high relative humidity record rather than the low relative humidity experienced during early July 1948, on the glacier.

Studies of local wind directions in the meteorological record for July did not clarify but complicated this anomaly. However, perusal of large scale air-mass movement from weather maps revealed that local winds were not representative of general air flow in this mountainous country where col currents and calms are common. Moreover, the direction of air-mass movement conformed to the day-by-day relative humidity record

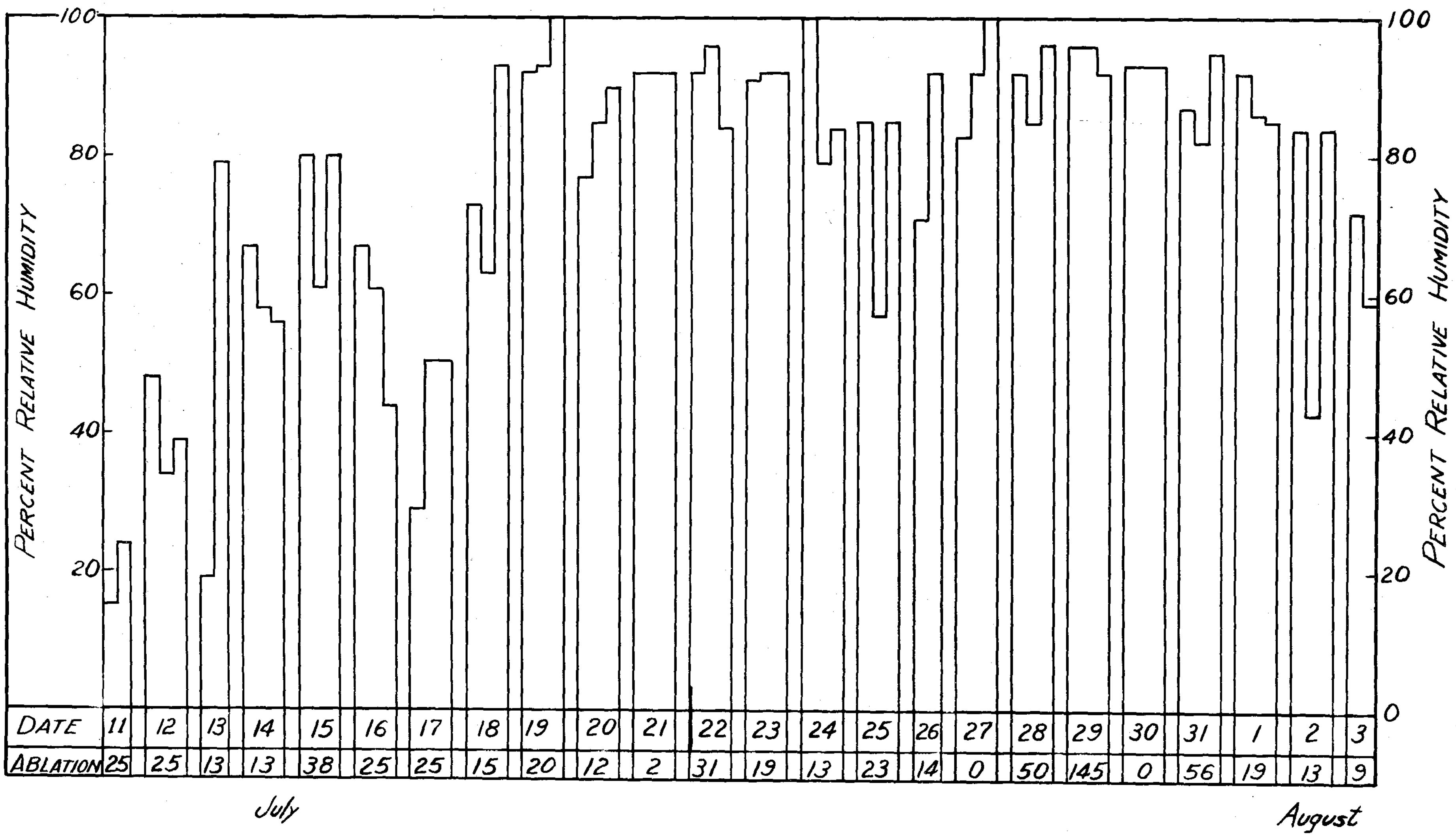

FIGURE 5.—The relative humidity record and the ablation record in mm. for July 11 to August 3.

without exception. When the main air flow was from the northeast, as it was during the major part of July, dry continental winds produced a low relative humidity. These low relative humidities showed a well-defined diurnal variation. They built up during the day, due largely to evaporation. The lowering of relative humidity at night was presumably related to a decrease in evaporation; for evaporation to occur at night additional heat is required to offset the heat lost through strong outgoing radiation. Moisture-laden air flow from the coast, or from a southwesterly direction, invariably brought a higher relative humidity and fog, if not precipitation; in fact, the prerequisite to all precipitation was a southwest air flow. Air masses moving from southwest to northeast brought variable cloudiness and usually fairly high humidities. It was during these latter stages that anomalous decreasing daytime relative humidities were experienced. Drying the air by condensing moisture on the snow surface may be an important factor here.

Thus the direction of air mass flow seems to be a determinant factor of relative humidity. As long as the air masses move from the northeast, as they did during the greater part of July, low relative humidities and considerable evaporation can be expected. However, considerable evaporation need not signify considerable ablation by evaporation. There is an important distinction; while the evaporation of ice is direct ablation, evaporation of melt-water is second generation ablation, and never the measured first generation ablation. It follows that periods of extreme evaporation, to affect ablation, must be periods of no melting.

Extreme evaporation was not the rule. The average wind velocity recorded was less than 5 miles per hour, and some of the lowest humidities were produced when wind velocity was at a minimum. The daytime gains in relative humidity were insufficient to indicate extreme evaporation.[4]

In summarizing it is believed that although evaporation was unusually high during July, its significance is less than would be expected from the very low humidity record. Statistically, evaporation's role in ablation is conjecture, and will remain so until additional meteorological studies are made.

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4. Crow, Loren W., Meteorologist Krick's Laboratories, Pasadena, California, oral communication.

Radiation versus Meteorological Factors

Although no measurements or estimates of the relative importance of radiation and meteorological factors were made, it is possible to make inferences concerning the dependence of ablation on these factors by comparing meteorological studies made in a similar environment.

Of the few glacier regions in which radiation and meteorological studies have been made, the Vatnajökull in Iceland is the only ice field where radiation conditions are similar to those on the Seward-Malaspina. The amount of incoming radiation available depends upon the altitude, latitude, cloudiness, shielding effect of the mountains, and the time of the year. All of these factors appear to be in general agreement on both ice fields.

On page 34 are the mean values of total diurnal radiation income (direct and diffuse) in the absence of clouds according to Kimball (1928, pp. 393-398). The values for the Hoffellsjökull and Heinabergsjökull Glaciers of the Vatnajökull have been computed by Ahlmann (1938, pp. 224-230), and the values for the Seward-Malaspina at sea level have been graphically interpolated from the tables and maps of Kimball, and the Smithsonian Meteorological Tables (1939, p. 225).

Daily Totals of Solar Radiation received at sea level in the absence of clouds. gr cal cm^2.

	May	June	July	August
Seward-Malaspina Lat. 60° 23' N., Long. 139° 53' W.	794	787	724	563
Vatnajökull Lat. 64° 25' N., Long. 15° 30' W.	720	750	675	525

The Vatnajökull has a similar maritime climate to that of south coastal Alaska as shown by the comparison of weather data in the table below. The geographic location of the Vatnajökull weather station, Holar, is similar to that of the Seward-Malaspina permanent weather station, Yakutat.

Weather Data (Holar Data from Ahlmann)

	Mean Temp. $^\circ$F., Holar 1936	Mean Temp. $^\circ$F. Yakutat 1936	Mean Cloud Cover, Yakutat	Mean Cloud Cover, Holar	1936 Precip. in Mean mm. Yakutat	Holar
ay	48	45	7.5	8	65	181
ne	51.8	50.4	7.5	8	85	50
ly	53.6	52.9	8	8.6	175	29
gust	53.0	53.2	7.5	7	110	144
				Total	435mm	404mm

The diurnal insolation, reduced for cloudiness was calculated by Ahlmann on the basis of a formula developed by A. Angstrom (1925, pp. 125-126) and the values developed in the first table. The formula is $Q_s = Q_o\ (0.25 + 0.75S)$, where Q_s is the average total radiation in the day, Q_o the total radiation income during a clear day, and S the hours of sunshine in the day, or the mean cloud cover in tenths subtracted from unity. It is a well established fact that cloudiness reduces the radiation less in northerly latitudes as a result of reduced vapor content in colder northern air masses (Olsson, 1936, pp. 105-106) To allow for this Ahlmann uses a (k) factor developed by Angstrom, which is assumed to be applicable to both Yakutat and Holar weather stations. A comparison of diurnal insolation reduced for cloudiness at Holar and Yakutat follows:

<u>Diurnal radiation reduced for cloudiness gr. cal/cm^2</u>

	Holar (from Ahlmann)	Yakutat
May	288	347
June	300	343
July	236	289
August	247	225

Now the actual amount of radiated heat received by the glacier depends upon the albedo, or reflecting power of the snow. The albedo varies from 60-90 per-cent (Wilson, 1941, pp. 182-195) depending upon the density, wetness, and purity of the firn surface.

That is, if the firn is dense, wet, or silty, the albedo is reduced accordingly. Presuming the albedo to be 75 percent and the radiation income available I, the absorbed radiation income would be (25 x I).

The effective radiation, or net radiation, depends upon the net effect of the absorbed and outgoing radiation. H. U. Sverdrup has developed a formula (1936, p. 44 and 1938, p. 226) for the outgoing radiation: R=230 (1-0.09 C), where R is the outgoing radiation and C is the cloud cover in tenths. By simple subtraction of R from the absorbed radiation, the net radiation available for ablation is determined. Using an albedo of 0.50 for ice Sverdrup calculated the monthly number of radiated gram calories received at Holar would melt x cm. of water and account for y% of the total ablation.

Computed percentages of ablation due to radiation and the meteorological factors are shown below for both Holar and Yakutat. For the sake of comparison ablation values for Yakutat are assumed to equal those at Holar, as they are <u>effect</u> and not directly <u>cause</u>. Holar results may be favorably compared with those calculated for the Yakutat region in the table following.

Computed monthly ablation percentages at Holar (Sverdrup) AND Yakutat (the author)

Month	Total Available Radiation (gm. cal/cm²) Holar	Yakutat	Ablation Due to Radiation Holar	Yakutat	Total Holar	Yakutat	Percent. Ablation Due to Radiation Holar	Yakutat	Meteorolog. Holar	Yakut
May	2480	3069	31	38	163	163	19	23	81	77
June	2580	2910	32	36	197	197	16	18	84	82
July	2046	2480	26	31	220	220	12	14	88	86
August	1209	1178	15	15	175	175	8.5	9	91.5	91

Observations from neighboring weather stations cannot compare in accuracy with those made on the glaciers in connection with the measurements of ablation. Nevertheless, one can safely extrapolate that the near sea level portions of glaciers in the vicinity of Yakutat, such as the Malaspina, are ablated overwhelmingly by meteorological factors except at the first of the summer when temperatures are so low radiation must play a major role. The assumption on page 36 of equal monthly surface ablation rates, does not alter the implications; for as has been shown, at sea level climatic factors determine the relative efficacy of radiation and convection, and these climatic factors can be treated alike at Holar and Yakutat. Admittedly, there is some difference in comparative ablation rates, but this should change the relative effects of radiation and convection very little. Other factors not mentioned play a subordinate role in radiation versus meteorological factors. For instance, the Malaspina is known to be in a more stagnant condition than the Hoffellsjökull and Heinabergsjökull. This implies a smaller albedo and favors radiation. However, because of its greater area near sea-level, the Malaspina would have a greater total ablation, which would favor the meteorological factors rather than radiation. Thus the subordinate factors attempt to cancel one another and the net resultant can disturb the radiation-convection ratio very little.

At 1500 meters above sea level on the Hoffellsjökull, Ahlmann and Sverdrup found that the influence of radiation on ablation increased to almost 50 percent during the middle of summer. This was a result of the clearer weather, the decreasing temperatures, and the greater amount of available radiation, all offsetting the greater albedo.

In view of the close agreement of radiation and meteorological percentages on the near-sea-level portions of the Hoffellsjökull and Malaspina, one might expect that a similar analogy could be drawn at the 1500 meter level on the Hoffellsjökull and our 5,720 foot camp-site on the Seward. However, monthly meteorological data at 1500 meters on the Hoffellsjökull is apparently lacking; Ahlmann's estimate of the influence of radiation is based upon several days observations at this altitude together with the Holar weather reports.

Ahlmann has found that ablation is 30 percent greater over ice than snow. This conclusion was reached after work on glaciers in Iceland and Scandinavia, and reflects the smaller albedo of ice compared to snow. However, there are several reasons why Seward Ice Field at the 5,720 foot level in 1948 could not have had an albedo 30 percent greater than that of ice. First of all no new snow was added during the summer months, and the density of the surface firn averaged 0.50 as compared to 0.016 for new snow and 0.89 for ice. As a result of high temperatures and low wind velocity the surface firn had an unusually low thermal quality, or percentage by weight, of ice. Of course, the pockets of silty firn that were uncovered by ablation would decrease the albedo also, but only the dominant clean firn will be considered here. Olsson, Eriksson, and Sverdrup have individually adopted an average albedo of 64 percent for wet clean firn as compared with 50 percent for ice. (1942, p. 41)

Since diurnal weather and ablation data were secured for a period at the Seward Airstrip Station, the ratio of radiation to ablation can be computed and compared with Ahlmann's estimate on the Hoffellsjökull.

For the period July 12-26 on the Seward the observed ablation was 288 cm., or multiplying this by an approximate firn density of 0.50, 144 cm. of water. By using Olsson's value of a (albedo) of 64 percent for wet firn the effective radiation for the same period was calculated from Sverdrup's formula ($a \cdot \Sigma - R$) to be 3,440 gm. calories/cm^2. This would melt ice to form 43 cm. of water and account for 22 percent of the observed ablation. However, as Kimball's values of radiation refer to sea level and must be increased to apply to this altitude, 22 percent is in reality a minimum value.

It is difficult, though, to conceive of radiation contributing almost 50 percent to ablation on the Seward as is hypothesized on the Hoffellsjökull. Even at solstice when insolation is at its maximum, it appears that the magnitude of the albedo and nocturnal radiation will offset insolation's potentiality. Owing to the large outgoing radiation the snow formed such a hard crust on clear nights, sometimes when the minimum temperature was above freezing, that the crust did not entirely thaw until at least an hour after the sun had reached the Airstrip Station.

Eriksson (1942, pp. 39-40) noted in North East Greenland that radiation from the snow surface was so great that the sum of radiated heat was negative. The resulting deficiency was compensated for by convective heat, but clear weather instead of bringing greater ablation, brought less ablation than during cloudy weather.

Figure 3 shows that this is not the case on Seward, and that the outgoing radiation must therefore not be of a magnitude to produce such a deficiency. In fact Figure 3 has shown a definite correlation between air temperature and ablation.

It is interesting to note in regard to the outgoing radiation that on all cloudy days during this period, July 12-26, the temperature never dropped below freezing during the night. The blanket of clouds reflected the outgoing radiation, thus preventing sub-freezing temperature. Significant is the fact that despite the ablation during these relatively warm nights, the total diurnal ablation was still less than on clear days with clear nights. A corollary to this is that ablation was greater during the daytime than at night, the greatest difference occurring on clear days. The only exception to this was when a new snow fell one day, and was entirely ablated that night.

The shielding effect of the mountains introduces a complicating factor that will certainly decrease the available insolation on the Seward in contrast to the relatively flat Vatnajökull at 1400-1500 meters. It is believed though that this may be treated as a minor factor on so large an ice field as the Seward.

General conclusions as to the roles played by radiation and the meteorological factors in ablation can now be drawn for 1948. These conclusions should not be given greater emphasis than is justified by the extension of data at hand; nevertheless, they should stimulate further work in these directions, and should serve as outer boundaries within which ablation factors may eventually be calculated to actual percentages.

There is also a definite space and time relationship between the relative importance of radiation and the meteorological factors.

The relative importance of radiation increases from the Malaspina up to the Seward Ice Field due, chiefly, to clearer weather, increased insolation, and decreasing temperatures. At solstice its contribution to ablation is probably greater than 22 percent, but is not believed to exceed 50 percent. The meteorological factors are overwhelmingly important on the Malaspina and retain their advantage over radiation on the Seward Ice Field.

As the summer opens radiation may hold an ephemeral edge over convection, because of the near-freezing air temperatures. Insolation is at its maximum at the solstice, but the importance of the meteorological factors decreases the relative efficacy of insolation, and since the temperatures remain high while the insolation decreases, radiation becomes increasingly subordinate to the meteorological factors. Only if the firn surface melts down to a dirty band while insolation values are still high, will radiation show an upswing and rival the meteorological factors in significance. In only small isolated parts of the Seward Ice Field could this have been true in 1948.

Rain

It has often been asserted that rain is one of the most important factors in ablation. (Agassiz, 1863, pp. 751-767 and 1864, pp. 56-65) However, Ahlmann's investigations on the Styggedal Glacier in Norway (1938, p. 224) revealed that rain increased the ablation on ice only when it fell at atmospheric temperatures above 45-47°F. Even in new deep snow, Ahlmann finds that rain is merely absorbed, increasing the water content of the snow. Angstrom (1933, pp. 264-271) shows that rainfall at an air temperature below 38°F. is usually mixed with sleet. Thus no appreciable heat becomes available for ablation.

The amount of melt resulting from rain depends upon the temperature and amount of precipitation, and the temperature of the glacier surface. If the glacier is isothermal at 32°F., the water melted from the snow can be computed by the following formula: Melt (in inches) = Rainfall in inches x (Temperature of the rain - 32°F.)/144 BTU.

Wilson (1941, p. 185) states that a thermometer wet bulb reading will not differ greatly from the temperature in a falling rain-drop. It is therefore possible to compute the ablation resulting from rainfall on the Seward Ice Field. Despite five periods of rain, ablation was negligible because wet bulb temperatures with one exception were always 32°F. or below during rainfall.

Even the exceptional case, a 0.25 inch rainfall at a temperature of 37°F., resulted in only .008 inches of melt. By the same method of computation it would take an 8 inch rainfall and a wet bulb temperature of 50°F. to produce 1 inch of melt water.

In dispersing the winter cold wave rain may play an important part. However it is believed that the effect of rain on ablation, though theoretically a heat source, is actually of minor importance above the firn line.

Indirect Ablation

Many glaciologists noted the effects of indirect ablation before Philipp (1912, p. 490) coined the term for the differential melting of ice in which foreign particles play an essential part. Poser (1933-34, pp. 1-20) has cited Kryokonitablation (dust ablation) as a better term for this melting process, but this term restricts the type and size of the particles and is not widely accepted.

Indirect ablation, in contrast with direct ablation, is accomplished by the conduction of heat through debris in contact with ice. Thin accumulations of dark particles absorb so much heat that the particles may perforate the surface of a glacier like a sieve. Hobbs (1922, pp. 166-167) cites an instance illustrating the efficacy and practical importance of ablation. During the construction of the Bergen Railway across Norway in 1909 it was necessary to clear great banks of snow. A layer of earth spread over the snow surface resulted in as much as six feet of indirect ablation in the course of a month and saved costly hand labor.

Direct ablation and indirect ablation cannot be measured separately. Indirect ablation may be of greater importance than direct ablation below the firn line, but it is almost always less important above the firn line. The increased indirect and direct ablation on the debris-covered and snow-bare ice below the firn line results in more rapid thinning of the glacier than in the region above the firn line.

While a thin cover of debris may promote ablation of the underlying ice, a thicker cover of coarse debris may promote ablation of the underlying ice, a thicker cover of coarse debris may impede ablation of the underlying ice. The size, color, and composition of rock fragments largely determines whether they will melt into the ice or stand out in relief. Sharp (1947, pp. 26-52) demonstrates that ablation moraine of varying thickness produces irregularities and instability but that a uniform cover serves to stabilize the existing ice topography. The removal of debris from a mound may result in a complete inversion of relief known as the <u>crevass</u> or <u>ablation cycle</u> (Gilbert, 1904, pp. 198-203).

Field observations on the Malaspina Glacier in 1948 show that indirect ablation is a waning factor in July in comparison with direct ablation. Leucocratic cobbles were observed on July 4 to have formed reentrants 18-20 inches deep in an ice face. On July 7 these reentrants were from 4-6 inches deep as a result of direct ablation. Other experiments (Brandt, 1932, pp. 84-93) serve to corroborate that in the early spring when insolation is the sole factor of ablation, indirect ablation proceeds more rapidly than direct ablation. Direct ablation gains the upper hand in the warm and cloudy summer months.

Net and Gross Ablation

Above the firn line there may be an appreciable difference between the total amount of water produced by ablation, and the amount removed from the glacier. The drained-off portion, or net ablation, may be less than the total ablation, or gross ablation in a temperate glacier as a result of four conditions:

1. Due to the retentivity of the snow and firn the thermal quality of the snow and firn will be increased when the winter cold wave sets in. The remelting of this ice the following spring or summer would, in any study, be recorded as ablation.
2. During the dissipation of the winter cold wave the melt-water, in percolating downward into the firn, will freeze when it reaches a depth where the firn temperature is negative. The remelting of this ice would also be recorded a second time as ablation.
3. Minute amounts of undrained melt-water are involved in the diurnal freezing of a surface snow crust. Remelting of the surface crust would include this, and it would be measured again as ablation.

4. If water collects in a glacier more rapidly than it can be carried away, a glacier water table may result. A discussion of such a water table follows in the next chapter.

Theoretically, the runoff from a glacier may be greater than the total ablation if the rainfall is greater than the amount of melt-water recorded twice as ablation. This exceptional case would call for a redefinition of the term net ablation.

If a glacier were isothermal at 32°F. the year-round, it would probably not be necessary to distinguish between net and gross ablation. The melt-water involved in the diurnal freezing and remelting of a surface crust and the difference of the total rainfall and amount of melt resulting from the rain are two minor factors, which would about offset one another.

Sverdrup's calculations (1935, pp. 71-72) on Isachsen's Plateau in West Spitsbergen show that one-fourth of the melt-water remained in the firn, while the rest was drained off. When meltwater is retained and refrozen in a glacier, it will subsequently be transformed into glacier ice. Not until this ice moves below the firn line will the remelting take place.

Below the firn line on a temperate glacier there is little reason to distinguish between net and gross ablation[5]. Since glacier ice is impermeable, melt-water travels directly to streams.

The quantities of melt-water that were measured twice on the Seward Ice Field are probably relatively unimportant, and do not affect the conclusions drawn from the total ablation values.

5. Ahlmann would still distinguish between net and gross ablation below the firn line, because his definition of net ablation includes the water removed from a glacier by corrasion and calving in addition to melting and evaporation.

Glacier Water Table

On July 19 at the Airstrip Station, water 16 feet deep was found standing 62 feet below the surface in a crevass. The height of the water in a second crevass, 160 feet south of the first crevass, was less accurately measured on July 23 to be 63 to 68 feet below the surface. On July 15 Sharp and Rigsby noted that the rate of thermal boring slowed at a depth of 64 feet and below that level continued at a constant rate. They pointed out that saturated firn would conduct heat away from the thermal boring apparatus at a faster rate than unsaturated firn.

These observations indicate that the firn must be saturated below the 62 to 68 foot level and that a glacier water table exists in the Seward accumulation area.

The chief factors which influence the formation of a melt-water table in the accumulation area of a temperate glacier are: (1) morphology of the accumulation area; (2) magnitude of gross ablation and rainfall; (3) structure and texture of the firn (4) impermeability of the underlying glacier ice.

All four factors have regulated the formation of the water table in the Seward accumulation area. The large flat-lying ice field with one outlet (and with observed ponding of water in crevasses at this outlet) induced a more rapid supply of melt-water than could be carried away. Vigorous ablation and minor precipitation in the form of rain were the sources of this supply. The permeability of the surface firn was favorable to the downward percolation of melt-water. The ice structures in the upper 10 feet of firn did not appear to retard the direction of melt-water flow. At greater depths thicker ice layers must impede melt-water flow to some extent. Impermeable glacier ice probably exists at a depth not far below the bottoms of the crevasses. Density measurements approach the density of glacier ice of 0.85 at a depth of 50 feet. Although melt-water can penetrate glacier ice through cracks and fissures, it cannot penetrate the ice itself. Thus, unless subglacial or englacial drainage is integrated the water can sink no further.

Internal Ablation

Ablation is not restricted to the surface of the glacier, but may also be internal. This internal ablation cannot be measured directly, because it occurs on the walls of crevasses and moulins, and in englacial or subglacial drainage tunnels.

In the course of summer crevasses are widened, and the subglacial tunnels are enlarged. More ice surface is made available to the effects of melting and evaporation. On stagnant glaciers such as the Malaspina, streams cut meandering englacial and subglacial courses which may later be abandoned. The united action of stream erosion and surface ablation initiates collapse of the tunnel roofs, thereby increasing the area for internal ablation. Above the firn line in buried crevasses and englacial chambers evaporation is probably the sole process of internal ablation.

Conduction of the heat flux of the earth may contribute some melting at the bottom of the glacier, as may the heat energy set free during glacier movements. Gilbert believed that the streams which flow from glaciers throughout the winter are supplied chiefly by basal melting. (1904, p. 214). Sverdrup (1935, pp. 80-82) shows in Spitsbergen glaciers that the earth's heat flux can only melt enough ice to produce about 7mm. of water per unit area per year, and that the heat generated by friction renders an amount of a similarly small order of magnitude. He, therefore concludes that the greater part of the water of these winter streams is derived from the surplus summer melt-water of the high-lying firn fields.

Theoretically the internal ablation of a glacier can be determined if gross ablation and surface ablation are known.

Thermal Phenomena of the Winter Cold Wave

During the summer, sub-freezing temperatures were experienced on the Seward Ice Field only at night. As the firn melted and the water percolated downward, there was temporary detention of melt-water by capillary attraction. Cooling of the surface firn at night froze some of this water to a depth of approximately 10 cm. forming the crust frequently observed. As the summer progressed and the mean diurnal temperatures decreased, the thickness of the crust grew to at least 25 cm. by August 31. It is believed that the incidence of the winter cold wave began about August 22, that is, sub-freezing temperatures after this date penetrated below the initial crust.

An elementary computation demonstrates that very little cooling is needed to lower the temperature of firn below 0°C., as compared with its heat of fusion. For example, to lower a pound of dry firn from 32°F. to 22°F., and assuming a specific heat of 0.48 at density 0.53, we find that 10 x 0.48, or 4.8 BTU are required, which is to be compared with 144 BTU for its heat of fusion, to convert a pound of water to the ice crystals comprising the firn.

Thus, freezing air temperatures easily penetrate dry firn. The depth of penetration is largely dependent on the degree of below-zero mean temperature and the amount of snowfall, which acts as an insulator to the firn.

The freezing and thawing of snow-crust can be considered a small-scale phenomenon of the glacier winter cold wave. Accordingly, the incidence and dissipation of the winter cold wave are from the surface downward. The rate at which the firn can absorb heat at the surface is limited only by the rate of heat-supply, but it must be remembered that the temperature of the firn (or ice) surface cannot rise above 32°F. By virtue of its change of state, that is, the production of melt-water, the surface firn absorbs all conducted or radiated heat from the air. When this melt-water percolates down into the firn, it freezes when it reaches the depth where the firn temperature is negative. As a result the water gives off its latent heat which raises the temperature at that level. Since little heat is required to raise the temperature of the firn to its melting point, with great ablation and heavy rains, the whole firn mass quickly becomes isothermal at 32°F. Sverdrup (1935, p.87) in his studies of the temperature of the snow-crust during freezing states, "...when every trace of the cooling in the preceding night down to a depth of 8 to 12 cm. disappears in less than half an hour then it is not surprising that every trace of the cooling during the preceding winter down to a depth of 10 to 15 meters disappears in one month."

The Seward Ice Field was already in this isothermal state when our party arrived upon it July 10. The temperature of the firn and ice was measured by Sharp and Rigsby at different levels to a depth of 200 feet. For every thermohm inserted between July 11 and July 17 the specially calibrated Wheatstone read 32° F. Thus every trace of the previous winter's cold wave is known to have disappeared by July 17 (probably much earlier), and the temperature was at the pressure-melting point.[6]

The Seward glacier complex is therefore of Ahlmann's temperate type (1933, p. 213) and Lagally's Warmen type (1932, p. 227) in a geophysical classification.

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6. The melting point of ice is lowered by pressure. 198 x 10^{-2} F.° for each 100 feet of ice, but this small increment cannot be read on the Wheatstone.

DIFFERENTIAL MELT DEPRESSIONS IN GLACIER ICE

Basins and Ice Wells

Differential melt-depressions filled with water and with debris-mantled bottoms are of two types, differing in shape and origin. The shallow basin type is an indirect ablation phenomenon; the vertical tube type has a more problematical origin. The basins may be abortive forms of the tubes, or an end stage in the coalescence of the tubes.

Agassiz (1863, pp. 751-767 and 1864, pp. 56-65) first mentioned differential melting depressions. He described crescent-shaped basins, which he called meridian holes from the accuracy with which they registered the sun's position. Under ideal conditions these basins have an east-west elongation with a steep south wall and a gently sloping north wall. Agassiz looked upon them as sundials of the glacier, recording the hour by the advance of the sun's rays upon them.

Engell's sonnenlöchern and Koch's mittagslöchern are terms synonomous with meridian holes. Nordenskiold's kryokonitshalen and Poser's kryoconitpfühle are irregular small basins, usually oval. As a result of the sun's unfavorable position to produce east-west crescent-shaped basins in high latitudes, these oval basins are thought to be high latitude equivalents of the meridian holes.

The aforementioned basins are measured in inches. Agassiz's baignoires (1867, p. 100) and a cryoconite pool described by Sharp (1947, p. 40) are examples of large irregular-shaped basins measured in tens of feet.

The second type of differential melting form, the kryoconitlöcher (ice dust hole), has been described by over 35 different authors and has been a subject of scientific curiosity since Norkenskiöld (1870, No. 10) first recognized them in Greenland in 1870. Hobbs (1922, P. 166-169) calls these holes, ice or dust wells, and his term ice well will be used in preference to kryoconitlöcher in this paper.

Ice wells as generally described are small cylindrical holes usually vertical and often circular. The concavity of the hole bottoms may give either a sharp or gradual decrease in the diameter of the holes with depth. Depths are reported as approximately 1 inch to 30 inches (Wegner, 1930, pp. 81-124), diameters from a fraction of an inch to 12 inches (Poser, 1933, PP. 1-5). The average ratio of diameter to depth is probably close to 1:6.

Types of Ice Wells Found on the Seward Glacier

Two contrasting types of ice wells were found on the Seward, those occurring underwater and those not occurring underwater.

The underwater ice wells were discovered August 13 in a pond at the margin of a rock spur 1½ miles east of the Nunatak Station. The perforated blue ice surface was from 4 inches to 2 feet under water. Due to an optical illusion the negative relief of the walls appeared positive; the wells looked like black cobbles and pebbles against the blue ice. There were no ice wells outside of the pond, probably because the surface was firn and not ice.

The wells were cylindrical, 1½ inches to 15 inches in depth and one half to 4 inches in diameter. The larger wells were inclined towards the sun at a uniform angle that appeared to be exaggerated by the refraction of the sun's rays in the water. The smaller wells were less inclined, some even vertical. Covering the concave bottoms of the wells was a mass of glutinous clay and silt. Several stages of formation were noted, but there were no stages of coalescence.

The other ice wells noted on the Seward Glacier were also found on August 13, on the southeastern slope of the Institute Glacier, about 300 yards from the underwater wells. The glacier ice had been bared by direct ablation in a spot where silt accumulations were localized. Although their position was on a 12°-15° slope, towards the sun, the wells were not inclined but vertical. The depths ranged from 2-6 inches and the diameters from one-half to 1½ inches. Most of the wells were approximately half filled with water. Some of the smaller wells were full of water; no well held less than 2½ inches of water. A cross section of a 7-inch well showed remarkable uniformity and symmetry. The diameter was 1¼ inches at the top and close to 1 inch near the base. The well bottom was concave upward and was coated with a thin silt accumulation that was thickest near the center. There were several samples of incipient coalescence of wells which may finally produce meridian holes.

Origin of Ice Wells

Writers are in agreement on the first step in ice well formation. Surface dust or silt, whether it be one particle or many, initiates indirect ablation, which proceeds at a greater rate than direct ablation. However, the deepening of the depression by indirect ablation cannot extend below the depth at which the bottom of the depression is continuously shaded from the sun. At least five theories have been advanced to explain the deepening beyond this critical depth.

1. Convection currents formed by heating water above 0°C. to a greater density, the warmed, heavier water sinking to the bottom of the well.
2. Radiation reflected by the walls of the ice well to the bottom of the well.
3. Direct radiation transmitted obliquely through the ice to the bottom of the ice well.
4. Living and decaying processes of organisms generate heat which deepens the wells.
5. Diffused rays falling parallel to the inclination of the ice wells; also doubly reflected diffused rays from an overcast reaching the bottom of the well.

Each hypothesis will be reviewed and where possible, critically analysed.

Convection Currents

No present-day writer favors this theory. Drygalski (1897, pp. 95-100) believes convection currents are not important because the water must be heated from 0°C. to its greatest density, 4°C., to sink to the bottom of the well. Steinböck (1936, pp. 1-21) shows this statement is literally incorrect because water heated any increment over 0°C. will sink. But Steinböck agrees with Drygalski that convection in water is not essential to the deepening of the wells.

By the time an original warmer and denser layer of water reaches the bottom of an ice well, it may well have lost its heat to the surrounding ice. Consequently, if convection currents were important, they would widen instead of deepening the wells. Furthermore, it is difficult to see how ice wells occurring under water could possibly have been formed by convection currents.

Reflected Radiation from Ice Walls

Several authors believe that diffused and direct rays reflected on the walls to the bottom of an ice well are of minor importance in the deepening of the well. Wagner (1938-39, pp. 129-137) rejects this hypothesis altogether. He insists that no reflection will take place from the walls into the water column, because the refractive indices of ice and water, 1.309 and 1.33 respectively, are almost equal. Never-the less, Wagner is apparently assuming that the ice well is either full of water or that the sun's rays strike the ice wall below the water line of the hole. The water line of the hole will usually be below the surface, unless direct ablation is proceeding at a more rapid rate than indirect ablation.

In Figure 6 lines a and c are sun rays which cannot be reflected at the water-ice contact, because their speed in ice is nearly that in water.

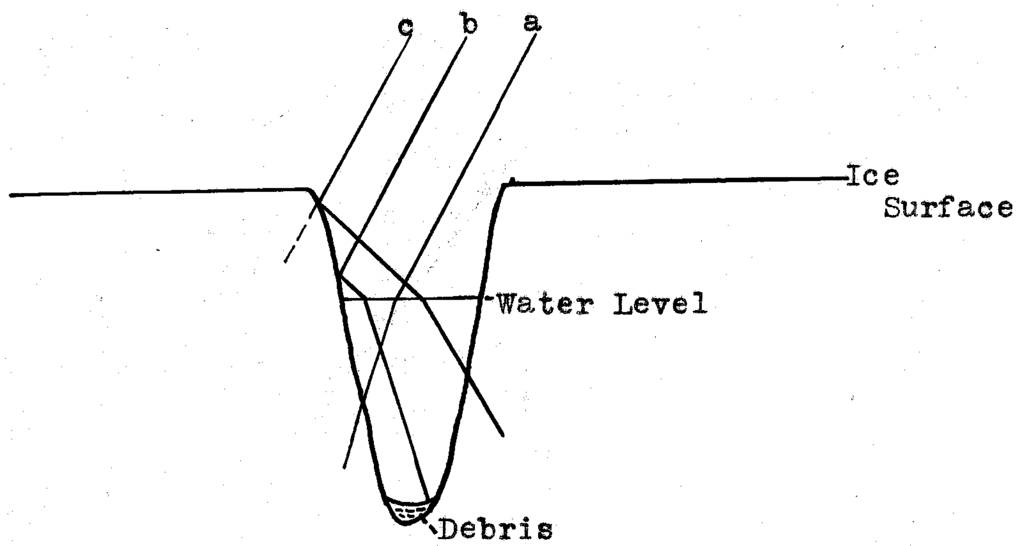


FIGURE 6.—Reflection of radiation from the walls of ice wells.

This is the reason Wagner discounts reflection on the ice wall. However, if a ray strikes the ice at a very low angle of incidence far above the water line, or at a higher angle of incidence close to the water line as ray b, with the aid of refraction at the water line, it can reach the silt at the bottom of the well.

Less this latter reflection mechanism be overemphasized it should be added that the absorption of radiation by the ice walls in addition to the reflection at the water surface will greatly reduce the amount of radiation reaching the silt.

Transmitted Direct Radiation

Philipp (1912, pp. 489-505) and Poser (1933-34, pp. 1-5) are the leading advocates of the hypothesis that direct radiation transmitted through the ice is responsible for the deepening of ice wells below the critical depth.

Philipp believes that radiant energy penetrates glacier ice at least 24 inches, the depth depending upon the absorption coefficient of the ice and the average inclination of the sun's rays. As a result of Philipp's assumption that the absorption coefficient is nearly constant in depth, the depth of penetration will depend on the incidence of the sun's rays. By further neglecting the refraction of the rays at the ice surface, he demonstrates that the depth of the wells is equal to $d = \sin(90-i) \times c$, where c is the thickness of the diathermic ice layer. Direct ablation will reduce this depth accordingly. For every latitude above 60° north the average depth of the ice wells can be determined mathematically according to Philipp.

In a rebuttal of Philipp's theory Steinböck argues that the sun rays are always inclined at such an angle in the Arctic, that most of them will be reflected from the ice; the remainder must travel such a great oblique distance to the bottom of the ice well, that their heat effects will be nil.

Drygalski has calculated that rays from the sun in its highest position at 70° North Latitude must travel 24-30 inches through the ice to heat the silt in an ice well 16-25 inches deep. Drygalski's most cogent argument against transmitted direct radiation was his observation that in the fall when the water in the ice wells was frozen over, the deepening of the holes stopped. Later in October when foehn winds brought in warmer weather and the ice melted in the holes, deepening started again. He concludes that the deepening must not be related to transmitted rays, but that the heat-source is from directly above the ice walls.

Although the transmissibility of ice to radiation is known in terms of its absorption coefficient, quantitative data are lacking on the depth that radiation enters ice. Of a given quantity of radiation reaching the glacier ice surface at least 50 percent will be reflected. The absorbed radiation reaches a depth dependent on the wave length of the rays and on the "ground-glass scattering effect" of the ice crystals. Blue-green rays, or short wave length radiation, will penetrate to greater depths than the yellow-orange and infra-red longer wave length radiation. The infra-red rays are the principal heat waves, and are absorbed in the melting of the surface ice. Thus very little heat can be carried below the surface. Although the blue-green rays enter clear ice to great depths, the effect of the ice crystals in glacier ice is to reflect these rays diffusely. The smaller the ice crystals, the greater will be the scattering effect. This scattering eliminates the little heat that the short wave length rays carry to great depths in water. It is difficult to imagine that appreciable amounts of "heat" radiation reach sufficient depths to account for the deepening of ice wells 26-30 inches in depth described by Drygalski (1897, pp. 95-100) and Wegener (1930, pp. 81-124).

Organisms

The debris in the bottom of the ice wells in Greenland was reported by Nordenskiöld to be of cosmic origin. Numerous analysis have proved him wrong; while some parts not classified may be of cosmic origin, the major portion of the debris is mineral and organic.

Living organisms have been found and studied in the clay and silt at the bottom of ice wells in Greenland. After the Nordenskiöld Expedition botanist, Berggren (1871, No. 8) described eight different algae in the ice wells, successive papers by Wittrock (1885) Drygalski (1897, pp. 95-100), Jensen (1928) and Steinböck (1936, pp. 1-21) have described the kryoconite flora and fauna. Wittrock was the first to seek an explanation for the deepening of the wells from the decaying processes of organisms. Steinböck has made the most recent botanical investigations, and believes that organisms may be a contributing factor below the critical depth.

He agrees with Drygalski that the kryoconite flora and fauna are adapted to their environment, and therefore are not an accidental nor ephemeral feature, but have existed in a fixed horizon (kryokonithorizonit) possibly through the ice epoch.

Since organisms are not always present in ice wells, especially at lower latitudes, they cannot be an important factor in the origin of the wells. Steinböck insists that organisms continue to live in the ice in the winter when the wells are frozen over; yet Drygalski has shown that the wells are not deepened when frozen over. Thus the heat generated by the living and decaying processes of organisms must have little or no effect.

Diffuse Rays

~~Wagner (1938-39, pp. 129-137) and~~ Steinböck (1936, pp. 10-12) believe this heat source is the most important in the deepening of the ice wells below the critical depth. The problem here is not one of access of the diffused rays to the bottom of the well, because the effective rays must fall at the same angle of inclination as that of the ice well. Proof is needed that the diffused radiation is of the intensity to account for the deepening beyond critical depth.

In higher latitudes where the altitude of the sun is low, diffuse radiation is often stronger than direct radiation. (Haurwitz and Austin, 1934, p. 160) The diffuse radiation received at the earth's surface was computed by Bauer and Philipps. (1934, p. 160) Particularly striking in their results was that in the zone 60° to 90° North, diffuse radiation was greater than the direct radiation, even at the summer solstice.

Measurements by Angström (1928, No. 3) of the diffuse radiation at Stocksund, Sweden, at 59.4° North Latitude should apply fairly well to the Seward Ice Field at 60.2° North Latitude. The diffuse radiation reaches a maximum in June, and is never less than 26 percent of the total insolation.

Approximately 50 percent of the direct and diffuse rays striking the ice surface will be reflected back to the atmosphere. Clouds will reflect a portion of this back to the earth's surface, ~~thus affording a portion of this back to the earth's surface~~, thus affording a second opportunity for the rays to fall at the angle of inclination of the ice wells. This source of reflected direct radiation has apparently been overlooked in the studies of ice wells.

Origin of the Ice Wells on the Seward

The inclination and underwater occurrence of the first wells described are two most unusual characteristics. Poser (1933-34, pp. 1-5) has been the only writer to report underwater wells, and these were nearly vertical. To my knowledge he is also the only writer who encountered inclined wells. His wells also dipped towards the south.

Why some wells are inclined while most are vertical is an unsolved problem. Von Engel (Poser, 1934, p. 1-5) theorized that all wells should be inclined, since silt on the north side receives more sun than silt on the south side of an incipient well. Experiments with artificial ice blocks in the April sun of Pasadena attest to the more important influence of vertical gravity settling. Inclined holes bored in the ice and filled with dark silt and water melted vertically downward instead of continuing their paths nearly parallel to the sun's rays. These results increase the difficulty of accounting for inclined walls.

The vertical wells showed no unusual features. In view of the rapid rate of ablation previous to observing the ice wells, it is difficult to imagine that indirect ablation was keeping apace with the direct ablation. Indeed, the fact that many of the smaller wells were filled with water suggests that they were decreasing in depth.

Diffuse sun rays are considered to be of major importance in the deepening of the ice wells beyond their critical depth. Doubly reflected direct rays also play a part. These diffuse and direct rays need not enter the ice wells along their axis of inclination. As shown in figure 6 , they may enter at a small angle to the walls and be reflected to the bottom of the hole.

Water acts as an insulator which keeps outgoing radiation to a minimum, and thus indirectly helps deepen the holes. The thicker the silt at the bottom of the well, the more heat can be absorbed and the less heat is lost.

As these observations were limited to one day the evolution of the ice wells is largely speculation. They may be ice wells reexhumed from the previous year. However, no evidence of secondary ice was seen in surface cross-section. Such filling may have been melted. If so the remelting, especially in the case of the deeper ones, could not have been induced by the residue of last year's silt at the bottom of the hole. The presence of silt in the holes leads to the inference that they are mainly, if not entirely, of current date.

MEASUREMENT OF MELT-WATER

Ahlmann and Sverdrup calculated the quantities of water which congealed, formed, and passed through the firn on Isachsen's Plateau (1933, pp. 290-291). Their computations are based upon ablation and precipitation data, and are the first of their kind.

Hughes and Seligman (1939, pp. 635-640) experimented with the movement of melt-water in depth on the Jungfraujoch in the Alps. They not only measured quantities of melt-water in collecting pans, but determined the direction, velocity, and nature of melt-water percolation.

Although the actual magnitude of melt-water flow is equal to the loss of water at the surface, depth measurements of water per unit area differ from the loss of surface water per unit area. Melt-water circulation through alternate firn and ice layers produces an uneven distribution of melt-water in depth. Thus the quantity of water measured in depth is not representative of the total melt-water produced at the surface. Moreover, only during the incidence and dissipation of the winter cold wave are depth measurements of total melt-water useful. These measurements furnish data on the freezing of melt-water in depth during the incidence of the cold wave and the production of melt-water during the dissipation of the cold wave.

Once the winter cold wave has been dissipated there is no better gauge of the quantities of melt-water passing through the firn than the amounts of surface ablation and rainfall.

These quantities of water will nearly equal the quantity of melt-water moving through the firn if the varying density of the ablated firn and snow is taken into account. Evaporation and internal ablation are minor complicating factors which are not measurable; however, they probably nearly offset one another.

On the other hand surface ablation measurements give no indication as to the nature and rates of melt-water movement through the firn; they are quantitative not qualitative.

The Isachsen Plateau and Jungfraujoch investigations represented two contrasting approaches to melt-water study. Ahlmann and Sverdrup emphasized surface ablation measurements, while Hughes and Seligman specialized in melt-water movement studies. It is unfortunate that these two equally important phases of melt-water study were not combined to supplement each other. For example, the melt-water figure of 0.1-0.3

$cc/cm.^2$/ hour at a depth of one meter on the Jungfraujoch (1936, p. 49) would be of greater significance were the rate of surface ablation known.

Melt-Water Movement Measurements on the Seward Ice Field

Melt-water studies, similar to those carried on by Hughes and Seligman (1939, pp. 635-640) were conducted at the Airstrip Station from July 21 to August 3 and to a lesser extent at the Nunatak Station from August 6 to August 14. Those made at the Airstrip Station are more significant and will be discussed first.

Nine spring brass collecting pans of 1439 $cm.^2$ were placed in niches excavated in the shaded south wall of the Airstrip Station 50-foot pit. Supplementary data, in addition to data illustrated in Figure 7 are tabulated on page 79. In relation to the Seward outlet the south wall of the pit was on the downstream side, but this fact has little significance on so broad and flat an accumulation area.

The pans as they appear in place are pictured in Figures 8 and 9. Meltwater gathering in the pans drained through a hole to a receiving vessel which was wired and clipped to the pan. This water was measured periodically in a graduate as illustrated in Figures 8 and 9. Records of these measurements are furnished in Appendix B.

Melt-Water Pan Data

Pan No.	Depth-July 21 Feet	Depth-July 21 Inches	Density of Firn July 18 - 24	Relation to Significant Ice and Dirty Layers
1	1	5	0.51	None
2	2	8	0.52	½"-1 inch irregular ice band 4 inches above
3	4	7	0.46	2-3¼ inch ice band 7 inches above
4	5	10	0.50	4 inch dirty layer 3 inches below
5	8	10	0.62	2 inch dirty layer 1 inch above
6	10	4	0.60	Several lensing ice layers below
7	12	0	0.62	Several lensing ice layers below
8	13	4	0.72	2-5 inch ice layer 4 inches below
9	16	2	0.71	None

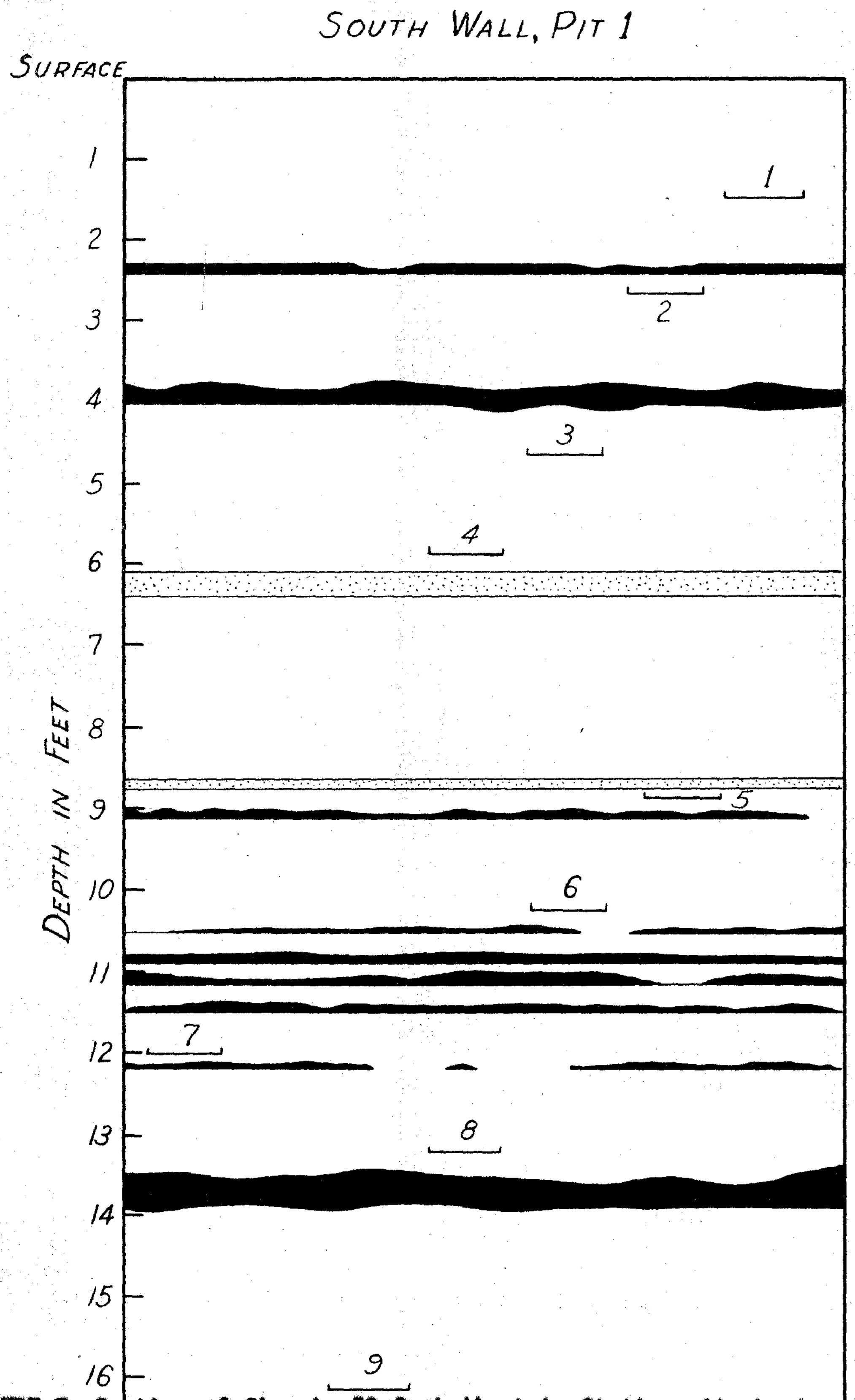


FIGURE 7.—Section of firn in 50-foot Airstrip Station pit showing distribution of melt-water pans in relation to firn stratigraphy. (Solid bands are ice bands; dotted bands are dirt bands.)

FIGURE 8.—Melt-water pans. (One pan is in place and the other holds a graduate.)

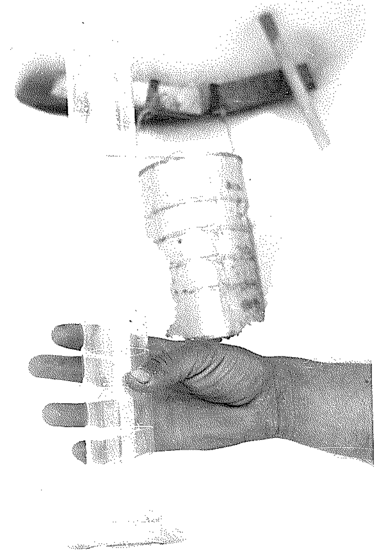
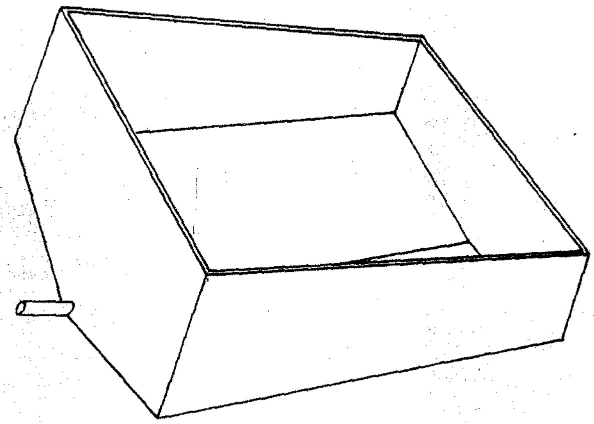


FIGURE 9.—Melt-water pan set-up.

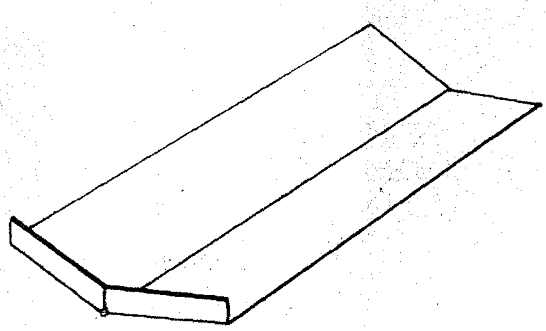
The size and shape of the pans are better shown in Figure 10. Here they may be compared with the collecting pans used by Seligman. The obvious difference in design between the two types of pans is the presence of four sides and a spout-outlet on the latter type. This difference not only changes the conditions of melt-water flow into the two pans, but necessitates different methods of inserting the pans in the firn.

Seligman completely buried his pans in the firn so that they would not be influenced by radiation, but by doing this he disturbed the conditions of the firn nearby. The melt-water that drained into the pan, and henceforth out the spout-outlet and through a rubber tube to a receptacle, represented the vertically falling melt-water to the partial exclusion of the horizontal component of flow.

The melt-water pans used on the Seward were designed to amend some of these difficulties, but in doing so, the new design introduced additional problems. Inasmuch as these pans were built without sides, they could be inserted by hand into the wall niche without disturbing the firn. Pans 1 to 6 were inserted in this manner. The firn in deeper horizons was so dense that it had to be removed before pans 7 to 9 could be inserted.



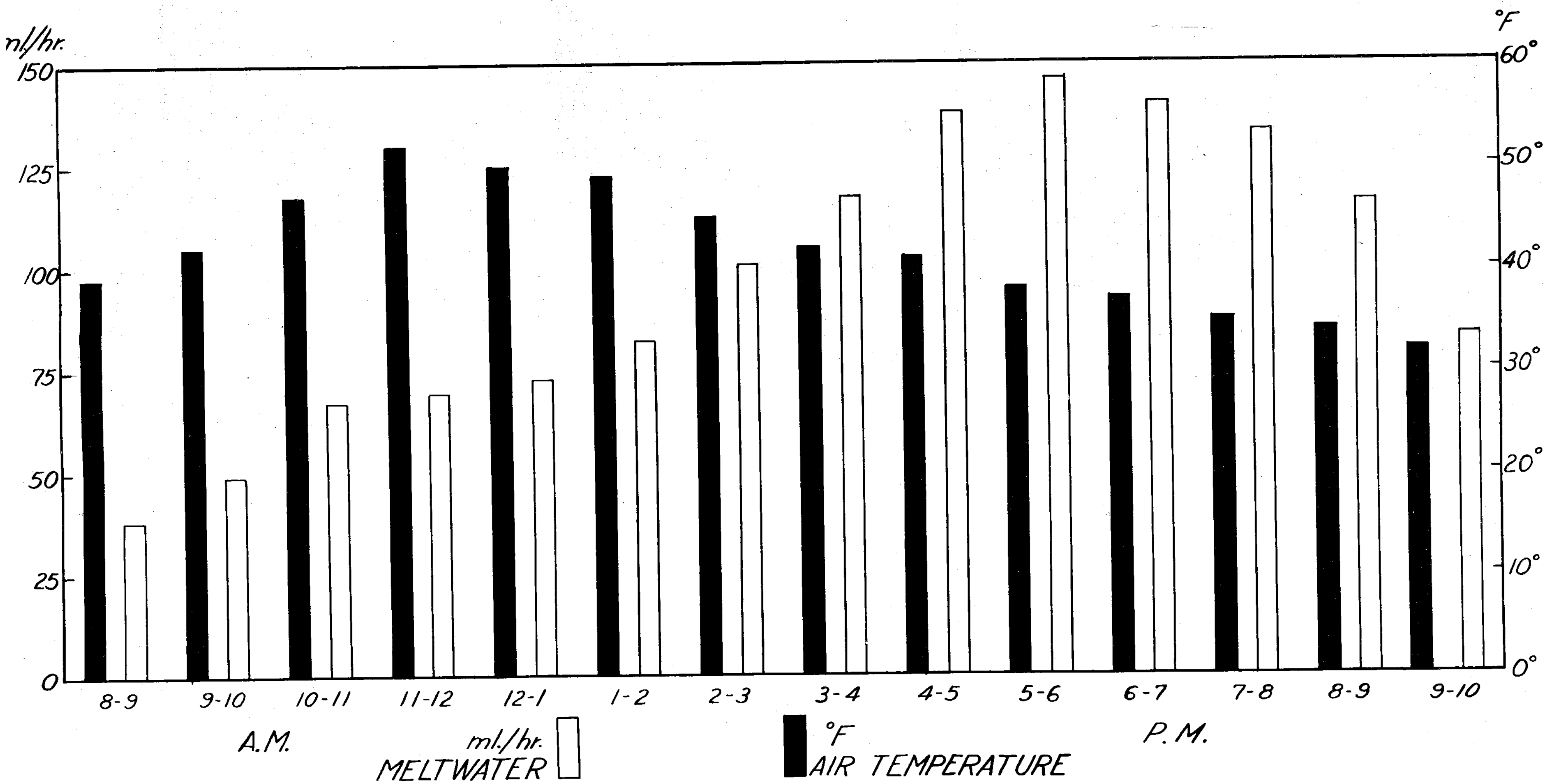
A.-Type of pan used by Seligman on the Jungfraujoch, 1938.



B.-Type of pan used on the Seward, 1948.

FIGURE 10.-A comparison of melt-water pans used on the Jungfraujoch and the Seward.

FIGURE 11.—A comparison of the average hourly melt-water collected from pans 1, 2, 3, 5, and 6 to the average hourly temperature during the hours 8 A.M. to 10 P.M. from July 24 to August 3.



In order that the melt-water would drain through the depression in the center of the pan and through the outlet, the pans were inserted at an angle ranging from 3 to 8 degrees. This inclination of the pans and the conduction of atmospheric heat through the exposed metal face caused the pans to slide out of position. Although wooden pegs were placed in the firn to brace the pans, they continued to slide out part way. Thus exact quantities of water per unit area could not be measured.

In addition to the movement of the pans the firn overlying the pans was melted away and melt-water was compelled to drip from a height ranging from a fraction of an inch to several inches above the pan. This abetted rather than restrained melt-water flow into the pan as will be shown in the following discussion.

The most important factor in the percolation of melt-water is the size of the firn grains and their interspaces. As with soil the smaller the grains or crystals the larger is the amount of liquid water that may be held up by capillary force. (Wilson, 1942, pp. 553-556). In view of the unusually high density of the surface firn on the Seward Ice Field, the capillarity of the firn was surprising. Experiments with dyed melt-water percolating through a section of firn and around, instead of through excavated niches indicated that the capillary attraction of the firn was greater than that of gravity.

Examination of Appendix B will show that after installing the nine pans in the 50-foot pit July 21, 2 to 7 days elapsed before a melt-water cycle was recorded for individual pans, with one exception; pan 4 produced water within 2 days, but as will be explained later, this was due to its position close to a dirt band. This significant lag in the production of melt-water is a direct consequence of the capillarity of the firn. As melt-water percolates downward to the metal pan it prefers to move by capillarity around the pan in preference to leaving the firn and draining into the pan.

Seligman (1936, pp. 273-284) contends, as do I, that capillary action is more effective in controlling water movement through a firn mass than is gravity, except when the melt-water has melted the snow grains and formed free fall channels or has saturated a layer of firn from which it can free-fall through space. The latter exception is the chief reason the melt-water pans at the Airstrip Station received water. The melt-water is held by capillary force over the roof of the niche until the firn in the roof becomes saturated and the capillary force is overcome.

Other evidence substantiates this theory. Four pans inserted in the walls of shallow pits at the Airstrip Station failed to produce melt-water for several days, if at all. Two pans located at 3 and 7 foot depths on July 29 produced no water until August 2. Two pans placed in another section of firn at 2 and 4 foot depths on August 1 had produced no water by August 4. Nevertheless, during these interims pans in the 50-foot pit at similar depths were receiving large quantities of water. Consequently, this lag in the production of melt-water was not a local phenomenon, nor was the capillarity of the firn which was responsible for the lag.

An already saturated one and a half inch thick layer of firn above a pan located in a shallow pit was sliced away during a day of extreme ablation. As a result it was two hours before gravity water supplanted capillary water and dripped to the pan.

Although a buried pan without sides receives the horizontal component as well as the vertical component of flow, in reality it probably collects much less melt-water initially than a buried pan of the same size with sides. The enclosed pan is able to trap capillary water. The free water content of the firn within the pan will increase until the cohesion between water molecules is greater than adhesion of water for the firn grains.

A pan with no sides offers no trap for capillary water. Although the firn may ultimately become saturated above the pan, the time interval will be considerably longer than with an enclosed pan. In addition, this lag will be considerably longer for a pan buried in the firn, than for the same type pan located several inches below the roof of a niche, because in the latter case the gravity effect overcomes surface tension of the capillary water.

In spite of this lag caused by capillarity the melt-water measurements in most of the pans are still significant. Once the firn above the pan became saturated, gravity water continued to flow during the period of observation. The accumulation of melt-water over the roof of the niche and the nocturnal freezing and melting of this saturated layer integrated and enlarged the crystal sutures, thus maintaining them.

The amounts of melt-water recorded differ from the actual melt-water draining to the receiving vessels in two ways.

Some of the pyrex beakers used as receiving vessels overflowed during early measurements of melt-water. Beakers of 600, 400, and 150 cc. capacity for pans 4, 5, and 6, respectively, were replaced on July 26 by cans with a capacity of 1430 cc. No overflows resulted after this substitution.

Freezing temperatures at night froze melt-water which had not drained from the pan to the receiving vessel. Inasmuch as it was not possible to measure the water content of this ice when melted, estimation of this amount of melt-water and its assignment to an earlier hour of formation may be in error. However, the amount of melt-water involved was never over 50 cc.

No pan was unduly influenced by its local environment with the exception of pan 4. The large rate of melt-water flow in pan 4 from July 22 to July 26 was due to its location above the zone of the large 4-inch dirt band. The dirty layer melted back by indirect ablation at a faster rate than the firn above or below it. This caused slumping and reduction of density in the 3 to 6 inches of firn directly above the band. Free-fall melt-water channelways developed in the slumped firn which lay in the zone of the pan. As soon as the exposed silt of the dirt band was dispersed and indirect ablation could no longer continue, slumping stopped, the free-fall channelways closed, and pan 4 ended its amazing rate of melt-water production as abruptly as it had begun.

Melt-Water Studies at the Airstrip Station

During July and August large quantities of melt-water percolated through the surface layers of the firn. Although melt-water figures tabulated in Appendix B are only relative, they serve two useful purposes.

1. They may be compared with the meteorological record and with the various periods of the day.
2. They yield information on the nature of melt-water movement.

Rates of flow ranged from 0 to 484 cc per hour in the nine pans. The rates were greatest in pans 3, 4, 5 and 6. Almost no melt-water accumulated in pans 7, 8, and 9. Thus the pans from 4 to 11 feet in depth made the most water and those below 11 feet the least. Pan 5 at 8 feet 10 inches received almost three times the amount of water received by any other pan.

Pan 1 gave signs of delivering large quantities of water before it was removed July 29. Although pan 2 was definitely hindered by the rope ladder stretching over it, it is surprising that it produced no water before it was removed July 30.

The fact that the upper firn layers produced less water than deeper firn layers is probably due to the greater capillary flow and less concentration of melt-water in the upper firn.

Melt-Water Studies at the Nunatak Station

Cursory melt-water studies were made in two pits on the east slope of the Nunatak Station from August 5 to August 15. Pans 1 to 3 were located the afternoon of August 5 at depths of 15, 29 and 56 inches, respectively, in the shaded southwest wall of a 10 foot pit. (See Figure 1, pit 3). Pans 4 and 5 were placed on August 6 at depths of 15 and 20 inches, respectively, in the south wall of a 4-foot pit. (See Figure 1, pit 2). Techniques of installation and measurement were similar to those described for the Airstrip Station studies. Quantities of melt-water received are recorded in Appendix C. No hourly rates of flow are supplied since no more than three measurements were made per day.

Several observations are significant. Melt-water pans 1 and 2 delivered water one-half hour after their insertion. Pan 5 produced the largest amount of melt-water recorded, 579 cc per hour on August 14 between 5 and 6 p.m. The average rates of melt-water flow were far greater than those recorded at the Airstrip Station. At night the rates of flow were surprisingly large; on August 8 an average rate of 93 cc per hour was recorded for pan 2. These aforementioned results are believed to be a direct consequence of the 3 to 5 degree slope, the position of the pans on the upstream side of the pit, the concentration of melt-water near the surface of the firn, and the unusually warm weather with only four nights of freezing temperatures.

Pan 2 was situated in the zone of the dirt band which was exposed at the surface 250 feet further up the slope. It is noteworthy that pan 2 received twice as much melt-water as any other pan.

Pans 4 and 5 repeatedly melted out of place so that no records could be obtained until August 14.

Correlation of Measured Melt-Water Flow with the Meteorological Record and the Time of Day.

In a climate like that of coastal Alaska, a glacier is impotent in its endeavor to reduce the air temperature to its own temperature, 32°F. At only three feet above the surface of the glacier the thermometer at the Airstrip Station recorded surprisingly high temperatures. Thus air temperatures stand out as the most significant index of melt-water production. This was indicated by Figure 3.

However, there is a time interval after diurnal maximum temperatures were reached before maximum quantities of melt-water were measured at depth. The table on the next page summarizes the average melt-water per hour collected in pans 1, 3, 5, and 6 and the average temperature for these hours from the data of Appendix B. Figure 11 graphically presents the data of the table on page 94 and illustrates the lag in daily melt-water circulation. The average maximum temperature was reached from 11 to 12 A.M.; the average maximum melt-water collected in pans 1, 3, 5, and 6 was recorded from 5 to 6 P.M.

Figure 12 shows the average hourly distribution of melt-water collected in pans 1, 3, 5, and 6, plotted from

Summary of Data in Appendix B

July 24-Aug. 3 Hour	Avg. Meltwater Flow (ml/hr.) Pan 1	Pan 3	Pan 5	Pan 6	Avg. of Pans	Avg. Temp. °F.
0800-0900	30	16	81	24	38	39
0900-1000	35	27	106	27	49	42
1000-1100	80	36	122	30	67	47
1100-1200	50	63	127	36	69	52
1200-1300	40	79	134	40	73	50
1300-1400	42	91	144	50	82	49
1400-1500	46	125	163	68	101	45
1500-1600	45	170	180	73	117	42
1600-1700	44	206	211	80	138	41
1700-1800	50	237	210	85	146	38
1800-1900	75	202	211	71	140	37
1900-2000	40	182	235	73	133	35
2000-2100	25	145	219	76	116	34
2100-2200	10	94	157	72	83	32

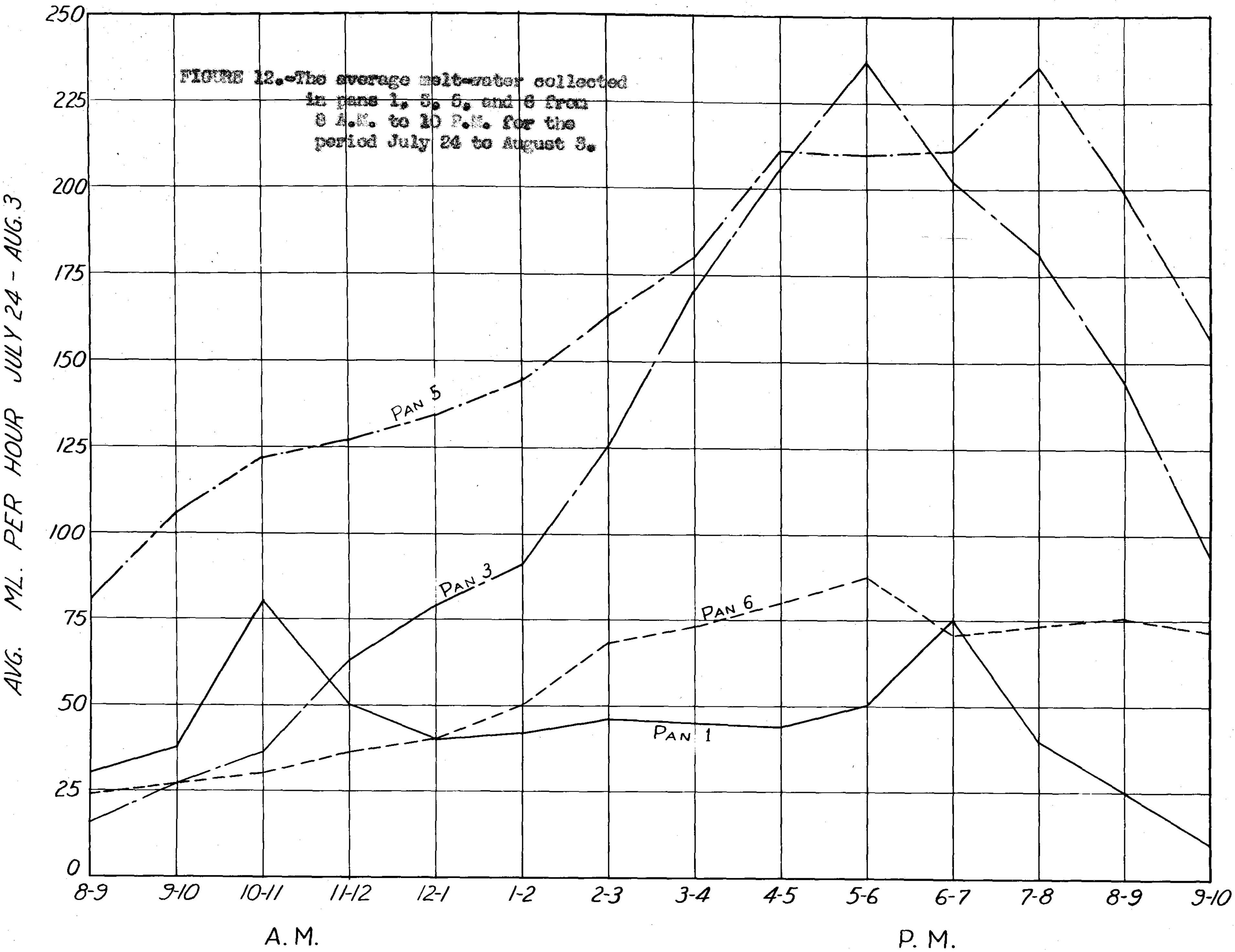


FIGURE 12.—The average melt-water collected in pans 1, 3, 5, and 6 from 8 A.M. to 10 P.M. for the period July 24 to August 3.

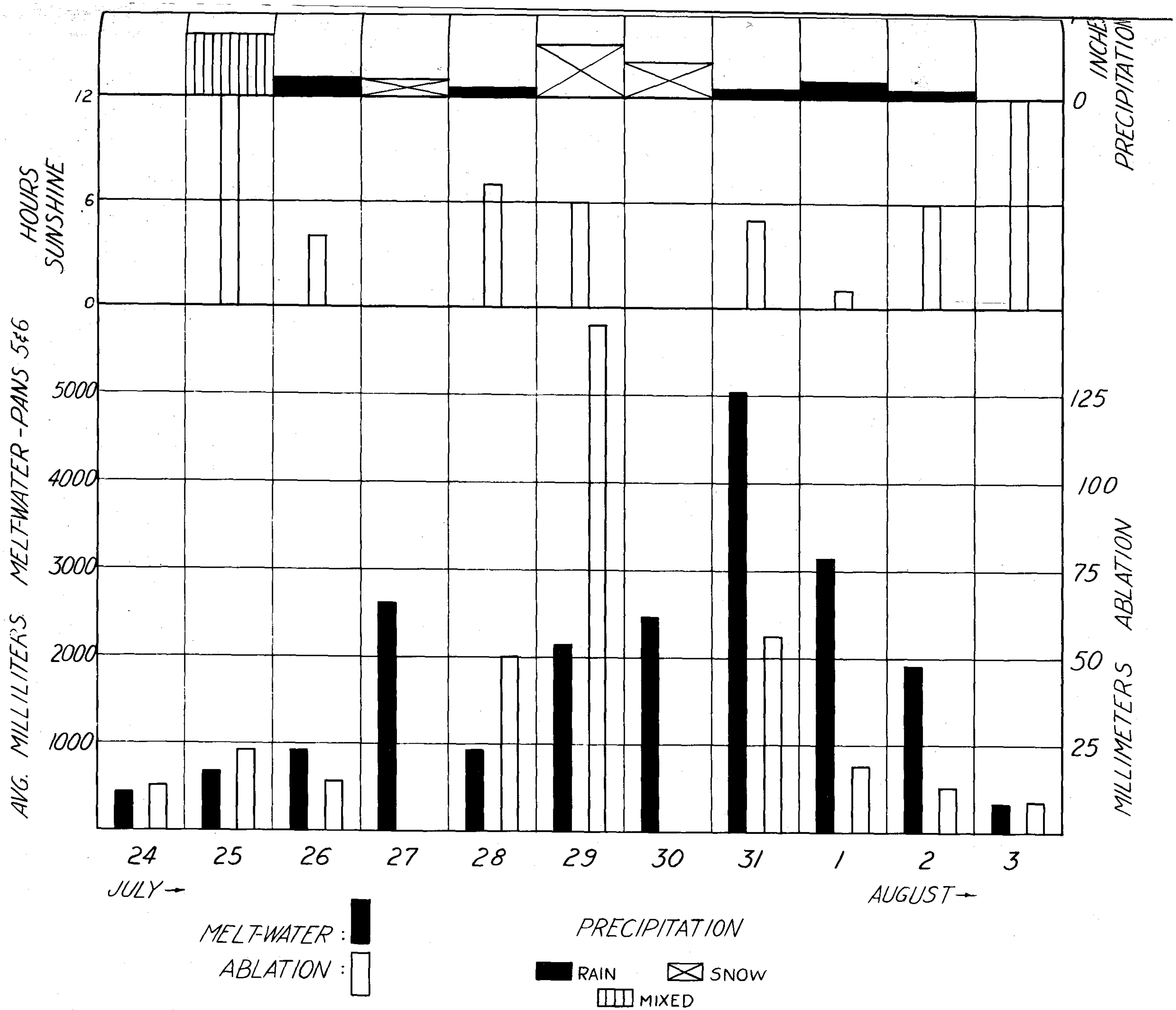


FIGURE 15.-Relation of melt-water totals of pans 5 and 6 to the ablation, precipitation and sunshine records.

the data of the table on page 94. Two peaks of melt-water flow were recorded for pan 1. The first peak was reached between 10 and 11 A.M. during the warmest part of the day. The second peak was reached between 6 and 7 P.M. when the much-thawed and loose-textured surface firn lost a large amount of its capillary water. Melt-water flow in pans 1 and 3 was more sensitive to air temperature changes than in the deeper pans, 5 and 6. The former pans show sharper and steeper peaks on the graph. Pans 5 and 6 continued to deliver large quantities of melt-water between 7 and 10 P.M. after their peaks were reached.

Pans 5 and 6 were the only pans receiving melt-water continuously from July 24 to August 3. Figure 13 compares the melt-water totals of pans 5 and 6 with the ablation, sunshine, and precipitation records. Melt-water figures were totaled for the meteorological day from 7 P.M. to 7 P.M. It is evident from this graph that increased ablation does not necessarily portend increased melt-water flow. On July 28 and 29 a snowfall was in a large part melted. Since snow is more easily melted than denser firn, a relatively large ablation figure was recorded in comparison to the amount of water melted from the snow.

In the same way large daily melt-water totals do not necessarily signify extreme ablation for the same day. On July 27 and 30 there was a large snowfall that melted as it fell. This resulted in relatively greater recorded melt-water than recorded ablation. On July 26 and 31, and on August 1 and 2 a rainfall produced relatively higher melt-water totals than ablation values.

The sunshine record of Figure 13 is based upon a maximum 12 hour sunshine day. Sunshine is shown to be a poor indicator of the efficacy of melt-water flow and ablation between July 24 and August 1. July 25 and August 3 were the only days to receive 12 hours of sunshine, and the lowest values of melt-water flow and ablation were recorded on these days. In view of the unusually poor weather and the short-11-day period of observation the sunshine record may not be of great significance.

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APPENDIX A - METEOROLOGICAL REPORT

Key to Nunatak Station Meteorological Report from July 4 to August 28

Column

1. Mean - mean Fahrenheit temperature
2. Max. - maximum Fahrenheit temperature
3. Min. - minimum Fahrenheit temperature
4. Time - time readings are made
5. Wet - wet bulb reading of sling pschrometer
6. Dry - dry bulb reading of sling pschrometer
7. R.H. - relative humidity
8. D.P. - dew point
9. Bar. - barometric pressure
10. Vel. - wind velocity in miles per hour
11. Dir. - windward direction
12. CC - cloud cover
13. Precip-precipitation in inches of water

    S. - snow

    I.S. - intermittent snow

    R. - rain

te	Mean	Max	Min	Time	Wet	Dry	R.H.	D.P.	Bar.	Vel.	Dir.	CC	Precip.
4		94	38	1900					24.02			0	
5	44.2	46	35	0700	36	44	49	26.5	23.98	2+	NE	1	
5		53.5	39.5	1330	37	48	35	23	23.86			3	
6	45	52	38	0700	34.5	42	51	26	23.82			4	
6		49	42	1300					23.82				
7	41.5	48	35	0730					23.92		SE	1	
8	47.5	50	37	0800					23.95			2	
9	44	53	34	0700					24.03	3-	W	1	
9		54	34	1900					24.01			1	
-10	40	47	31	0700					24.04			2	
-10		49	37	1900					24.00		NE	2	
-11	43.5	49	34	0700	37	54	15	10	23.98	5-	E	1	
-11		52	39	1300					24.00	2-	S	0	
-11		53	38	1900	31	43	24	17	24.00	5-	N	0	
-12	49.5	53	38	0700	35	43	48	26	24.01	5+	E	1	
-12		61	42	1300	37	49	34	22	24.02			1	
-12		61	42	1900	35	45	39	22	24.02	5+	E	2	
-13	50	61	41	0700	31	44	19	4	24.07	5+	N	4	
13		61	39	1900	36	41	79	35	24.15			10	
-14	48.5	61	36	0700	37	42	67	32	24.159	4-	SE	4	rain 0.25
-14		52	37	1300	41	48	58	34	24.18	2-	SW	1	
-14		52	37	1900	39	46	56	31	24.15	5-	S	8	
-15	44	52	36	0800	42	45	80	39	24.15	4-	S	9	
-15		53	36	1300	41	47	61	34	24.15	2-	NW	6	
-15		52	35	1900	40	44	80	38	24.12	2+	N	7	
-16	42.5	53	28	0700	38	43	67	33	24.05	5+	E	1	
-16		57	40	1300	39	45	61	32	24.01			2	

…te	Mean	Max	Min	Time	Wet	Dry	R.H.	D.P.	Bar.	Vel.	Dir.	CC	Precip
16	50.5	57	40	1900	37	46	44	26	23.99	3+	NE	2	
17		57	39	0730	39	50	29	29	23.94			0	
17		61	40	1300	43	52	51	35	23.95	3+	NE	0	
17		62	40	1900	43	52	51	35	23.94	2+	SW	0	
18	49.5	61	39	0700	40	44	73	34	23.90	5+	SW	8	
18		50	39	1300	42	48	63	36	23.83	2+	SE	10	
18		50	38	1900	39	40	93	38	23.82	3+	N	10	rain
19	40.5	50	31	0700	33	34	92	32	23.77	3+	NE	10	snow 0.75
19		36	31	1300	30	34	93	25	23.78	2+	W	10	I.S.
19		39	31	1900	32	32	100	32	23.71	7+	SW	10	I.S. T
-20	36	40	28	0700	33	36	77	30	23.60			4	
-20		43	32	1300	36	38	85	34	23.60	5+	NW	4	
-20		44	32	1900	33	34	90	32	23.60	5+	W	10	I.S.
-21	37	44	30	0700	32	33	92	32	23.64	5+	W	10	S 0.7
-21		41	32	1300	39	40	92	38	23.65			10	S
-21		41	32	1900	34	35	92	32	23.67	3+	E	10	S 0.3
-22	38	41	31	0700	35	36	92	34	23.67	5+	NNW	9	
-22		45	32	1300	41.5	42	96	41	23.69	5+	NNW	9-	
-22		40	32	1900	34	36	84	32	23.72	5+	NNW	10	
-23	36	36	32	0700	34	35	91	33	23.69	7+	SW	10	
-23		39	33	1300	35	36	92	34	23.71			10	
-23		40	33	1900	34	35	92	33	23.70	5+	S	10	S
-24	36	40	30	0700	32	32	100	32	23.64	5+	WSW	10	S 0.2
-24		40	30	1300	38	41	79	35	23.69	5+	N	10	
-24		42	30	1900	35	37	84	33	23.71	5+	W	10	
-25	38.5	39	30	0700	38	40	85	36	23.74	5+	SSW	9-	I.S. 0.7
-25		45.5	34	1300	41	48	57	34	23.82			5-	
-25		47	34	1900	38	40	85	36	23.90	5+	E	0	

e	Mean	Max	Min.	Time	Wet	Dry	R.H.	D.P.	Bar.	Vel.	Dir.	CC	Precip
-26	38.5	47	30	0700	37	41	71	32	23.83	5	E	0	
-26		44	32	1900	33	34	92	32	23.87	5	SW	10	
-27	36.7	44	30	0700	31	33	83	29	23.74	8	W	10	I.S. 0.
-27		33.5	30	1300	31	32	92	30	23.71	4	W	10	I.S.
-27		33.5	29.5	1900	30	30	100	30	23.70	5	W	10	I.S.
-28	33.5	33	27	0700	32	33	92	31	23.78	5	E	10	I.S.
-28		37	28	1300	37	39	85	35	23.87	5	W	10	
-28		40	28	1900	28	30	96	29	23.92	5	W	10	
-29	35	40	28	0700	32	32.5	96	32	23.88	6	NE	10	I.S.
-29		40	32	1300	40	41	96	39	23.84	8	W	10	I.S.
-29		42	32	1900	34	35	92	33	23.91	5+	WSW	10	I.S.
-30	35.5	41	30	0700	33	34	91	32	23.98			10	S. 1.0
-30		36	30	1300	33	34	91	32	23.97	5		10	S
-30		36	30	1900	32	33	91	31	23.97	5+	NE	10	S and R
-31	36.2	34	30	0700	34	35.5	87	32	23.99	7	N	8	Prec. en 0.9
-31		42	30	1330	31	33	82	29	23.73	5	E	10	
-31		43.5	29	1900	34.6	35	95	34	23.84			7	I.S & R
-1	36.2	43	29.5	0700	34	35	92	33	23.88	3	S	10	S .2
-1		43	33	1500	39	41	86	37	23.95	5	SW	10	
-1		43	33	1900	37	39	85	35	23.98			10	
-2	35	43	32	0700	32	24	84	30	24.00	5-	NE	7	
-2		45	24	1300	36	45	43	26	24.01	5	N	4	
-2		46	34	1900	34	36	84	32	24.02	5	N	9	
-3	37.5	47	28	0700	32.5	36	72	28	24.01	10	N	0	
-3		47	34	1900	36	42	59	29	23.98	7	NW	1	
-4	42.5	51	34	0700	33	41	45	22	23.92				
-5	41	48	34	0700	33	38	62	27					
-5		54	20	1900	33	36	76	29					

Date	Mean	Max	Min	Time	Wet	Dry	R.H.	D.P.	Bar.	Vel.	Dir.	CC	Precip
3-6	38.5	48	31	0700	35.5	36	80	31					
3-6				1900	34	42	46	29					
3-7	41	52	30	0700	33	37	68	28					
3-7				1900	31.5	35	62	27				10	rain,slee
3-8	37.5	45	30	0700	33	33	100	33				10	
3-8				1900	35	36.5	88	34					
3-9	35		32	0700	33	34	91	32					snow
3-9				1300			100	33	23.94	4	W	10	snow
3-9		47	23	1900				31	23.89			2	snow sto 4.3
3-10	36.5	43	27	0700	32	35	75	28	23.92	4	E	5	
3-10				1300	38	45	66	28	23.92	4	W	4	
3-10		46	32	1900	33.5	38	65	28	23.92	4	E	0	
3-11	40	48	32	0700	34.5	38	73	30	23.78			10	
3-11				1300	34	41	51	25	23.87			10	
3-11		48	35	1900	35	45	37	22	23.88	3	W	2	
3-12	42.5	46	36	0700	35	42	58	26	23.89	5-	E	3	
3-12				1300	35	45	37	22	23.95	1	S	6	
3-12		49	36	1900	38	46	50	29	24.01	4	E	2	
3-13	47.5	54	39	0700	38	44	60	31	24.06	6	E	2	
3-13		56	41	1900	39	46	56	31	24.09	10	E	5	
3-14	50	57	42	0700	47	51	76	44	24.10	12	NW	2	
3-14				1300	44	56	39	32	24.10			2	
3-14		59	41	1900	46	56	49	37	24.04	13	E	4	
3-15	53.5	59	41	0700	45	55	48	43	23.03	23	E	4	
3-15		66	41	1900	42	51	49	32	24.05	10	E		
3-16	47.5		41	0700	41	48	57	34	24.05				
3-16		54		2100	38	39	92	37	23.93				
3-17	36.5		31	0700	31	31	100	31	23.85			10	snow 0.6

-8

Mean	Max	Min	Time	Wet	Dry	R.H.	D.P.	Bar.	Vel.	Dir.	CC	Precip.
	42		1900	32	36	68	27	23.94				
48			0700	32	38	55	24	23.95				
	48		1900	34	37	77	31	23.87				
38		31	0700	33	33	95	33	23.80				
	46		1900	35	38	77	32	23.88			9	
41		32	0700	34	37	77	31	23.94			6	
	50		1900	33	36	76	29	23.94			3	
40	50	30	0700	32	33	87	31	23.97			7	
	50	34	1300	41	42	89	40	24.02	5	N		
	44	34	1900	35	35	96	35	23.94				
33		31	0700	32	33	90	30	23.72				
	36	34	1300	34	34	100	34	23.58	12	SE	10	
30			1300	27	31	62	22	23.51	13	E	7	
	33	27	1900	25	28	69	20	23.49	12	S	10	
30	33	25	0700	19	21	61	15	23.55	3	W	4	
	33	20	1300	27	29	80	24	23.65	2	N	0	
	35	20	1900	26	29	70	21	23.68	5	W	0	
28	34	19	0700	20	24	53	12	23.73			1	
			1300	30	33	73	26	23.74	4	W	1	
	37		1900	25	26	89	23	23.70	4	W	4	
28	37	19	1300	31	31	100	31	23.62	5	W	10	
	34	26	1900	23	25	77	20	23.60	4	E	3	
31		21	0700	22	24	76	18	23.68			0	
			1300	30	31	90	29	23.68	2	S	1	
	41	21	1900	29	30	90	28	23.78			1	
30	41	23	0700	25	31	33	2	23.84			10	
			1300	30	31	95	30	23.80	6	N	10	
	41	20	1900	29	31	77	26	23.78	2	E	10	

			Nunatak Station			Airstrip Station				
te	Abl.	Accum.	Mean	Max.	Min.	Mean	Max.	Min.	Sun	Precipitation
12	25.4		49.5	6k	38	49	61		12	
13	12.7		50	61	39	40	56	24.5	2	
14	13.0		48.5	61	36	47	65	29.5	10	Rain 0.25
15	38.1		44	53	36	47	65	29.5	7	
16	25.4		42.5	57	28	43	57	29	12	
17	25.4		50.5	62	39	37	49	24	12	
18	15		49.5	61	38	38	51	28	1	Rain and Snow
19	20		40.5	50	31	38	47.5	32	8	From 7-17=0.75
20	12		36	44	28	47	65	28	4	Snow
21	2		37	44	30	42	57	28	0	From 7-20=1.00
22	31		38	45	31	47	61	33	12	
23	19		36	40	32	45	58	33	0	
24	13		36	42	30	42	52	32	0	
25	23		38.5	47	30	43	54	33	12	Rain and Snow,0.70
26	14		38.5	47	30	43	64	23	4	Rain 0.20
27	0	50	36.7	44	29.5	40	48	32	0	Snow 0.20
28	50		33.5	40	27	34	56	12	8	Rain 0.10
29	145	160	35	42	28	39	48	30	6	Snow 0.60
30		120	35.5	41	30	38	49	30	0	Snow 0.40
31	56		36.2	43.5	29	44	56	33	5	Rain 0.10
1	19		36.2	43	29.5	46	59	32	1	Rain 0.20
2	13?		35	46	24	43	60	26	6	Rain 0.10
3	9		37.5	47	28	38	57	22	12	

APPENDIX B MELT-WATER PAN DATA - AIRSTRIP STATION

Melt-Water Pan Data at Airstrip Station from July 24 to August 3.

Key: 1. Plus sign indicates overflow.

2. First column is total melt-water collected in pan; second column is hourly average of melt-water collected.

3. T = air temperature.

	Temp.	1	1	1	3	3	4	4	5	5	6	6	7	8	9
22/10	58	17					137	293							
45	56						161	275							
00	39	—					630-	193							
Total		17					928								
23/15	43						616-	46							
00	45						—				50	2		16	
Total							616				50			16	
24/30	41						650-	55	425-	35	170-	14			
30	45	5			12								7		
00	39	—			—		59	6	278	29	26	3	—	17	
Total		5			12		709		703		196		7	17	
25/00	39						650-	47	425-	35	170-	11			
00	44								415-	52	158-	19			
00	39						515	47	416-	39	149-	50			
Total							1165		1256		477				
26/00	54	10							220-	14	170-	10			
00	55	136							425-	106	170-	43			
00	40	38							55	55	64	64			
00	38						23	2/3			51	53			
05	38								117	110					

	Temp.	1	1	1	3	3	4	4	5	5	6	6	7	8	9
26 (cont.)															
00	36	171													
45	34	53							730	199	333	87			
30	33	—					—		149	199	90	120			
Total		408					23		1696		878				
27															
30	37	23					5	1/5	892	75	765	64			
00	40	58							485	323	136	91			
15	48	155							151	121	87	70			
15	37								305	102	258	86			
00	37	85							271	155	178	102			
15	32	72							420	186	198	88			
15	31	91							320	160	268	134			
00	30	8					—		139	172	99	132			
Total		492					5		2983		1989				
28															
45	30								78	21	160	10			
20	35								369	43					
40	45								320	240					
45	50				97				361	120	164	164			
00	42	850-	44		290	105			232	103					
00	36	115	115		151	151			140	140	42	11			
00	33	132	33		235	59			650	164	90	23			
Total		1097			773				2150		456				
29															
30	31								880	98	53	5			
30	34	55	5						138	69	11	52			
00	45								589	131	55	12			
30	39				265	15			525	210	72	29			
45	38				265	212									
30	37				232	309			862	431	125	62			

	Temp.	1	1	1	3	3	4	4	5	5	6	6	7	8	9
-29 (cont.)															
830	37				247	247			428	428					
000	36				210	140	7		600	400					
100	36				80	80			417	417	284	81			
200	32	—			40	40	—		244	244	54	54			
Total		55			1339		7		4683		654				
-30															
100	31				28	9			579	193	105	35			
600	34								582	116	53	11			
800	43								283	141	17	9			
840	44								54	81					
100	45						4		254	109	35	12			
400	36				17	15			287	96	64	21			
630	34				105	42			534	214	67	27			
730	34				79	79			225	225	30	30			
000	35				270	108			760	304	164	66			
130	34				272	181	110		517	345	190	127			
Total					771		114		4075		725				
-31															
130	34				255	51	130	26	757	131	472	94			
330	35				260	65	150	38	810	240	380	95			
330	42				102	50			352	176	160	80			
945	56				224	100			473	210	165	73			
145	46				216	216			296	296	107	107			
100	52				260	115			647	288	360	160			
100	44				260	130			880	440	780	390			
700	43				453	453			616	616	383	383			
300	42				360	360			484	484	314	314			
00	34				500	250	40		812	406	301	151			
00	?				156	75	106		346	173	320	160			
Total					3046		426		6473		3742				

	Temp.	1	1	1	3	3	4	4	5	5	6	6	7	8	9
8-1															
0645	36								906	104	306	35			
0700	36				158	18			147	114	45	36			
0800	39								128	128	33	33			
0900	40														
1000	45				65	21			116	116	34	34			
1100	54				60	60			179	179	55	55			
1200	57				120	120			248	248	65	65			
1315	54				260	208			285	228	60	48			
1400	52				223	297			214	285	75	100			
1600	45				662	331			576	288	227	113			
1700	42				295	295	13		305	305	140	140			
1800	40				185	185			275	275	95	195			
2000	37				285	143			578	289	200	100			
2100	37				85	85			260	260	80	80			
Total					2398		13		4217		1415				
8-2															
0800	40				200	18			912	83	75	7			
0900	43				25	25			75	75	8	8			
1100	51				25	13			175	87	6	3			
1400	60				150	50			440	147	35	12			
1530	51				217	145			298	199	35	23			
1630	50				39	39			126	126	42	42			
1730	39				56	56			125	125	67	67			
1830	37				157	157			120	120	157	157			
1930	36				115	115			115	115	55	55			
2130	27				157	79			250	125	85	42			
Total					1141				2636		565				

	Temp.	1	1	1	3	3	4	4	5	5	6	6	7	8	9
-3 0900	41				44	3½			343	31	5	½			
1000	43				28	28			50	50	7	7			
1100	46				12	12			66	66	7	7			
1230	48				14	9			101	67	9	6			
1330	46				64	64			169	169	14	14			
1630	42				115	38			150	50	17	6			
1930	32				354	118			148	49	12	4			
	Total				631				1027		71				
Grand	Total	2,074			10,111		3,708		31,899		11,218				

APPENDIX C** MELT-WATER PAN DATA--NUNATAK STATION

Date	No. 1	No. 2	No. 3	No. 4	No. 5
8-6 0930	78	542	455		
1445	425	700			
1845	215	565			
Total	718	1807	455		
8-7 0830	2	237	565		
1530	424	358	313		
1815	132	257	30		
Total	558	852	908		
8-8 0900	762	1365	49		
1200	15	380	0		
1815	365	1298	0		
Total	1045	982	25		
8-12 0830	580	390	23		
1710	791	1202	0		
Total	1371	1592	23		
8-13 0800	217	551	5		
8-14 1000	409	1209	325		
1230	686	910	402		
1515	717	345	805		
1710	232	484	226	360	480
1800	150	290	725	395	483
Total	2194	4239	2483	755	963
Grand Total	7773	14546	3992	755	963

APPENDIX C - MELT-WATER PAN DATA - NUNATAK STATION

Date	No.1	No. 2	No. 3	No. 4	No. 5
8-6 0930	78	542	455		
1445	425	700			
1845	215	565			
Total	718	1807	455		
8-7 0830	2	237	565		
1530	424	358	313		
1815	132	257	30		
Total	558	852	908		
8-8 0900	762	1365	49		
1200	15	380	0		
1815	365	1298	0		
Total	1142	3043	49		
8-9 1220	263	743	29		
8-10 0800	265	737	15		
8-11 0830	465		25		
1710	580	982	0		
Total	1045	982	25		
8-12 0830	580	390	23		
1710	791	1202	0		
Total	1371	1592	23		
8-13 0800	217	551	5		
8-14 1000	409	1209	325		

Date	No. 1	No. 2	No. 3	No. 4	No. 5
8-14 1230	686	910	402		
1515	717	345	805		
1710	232	485	226	360	480
1800	150	290	725	395	483
Total	2194	4239	2483	755	963
Grand Total	7773	14,546	3992	755	963

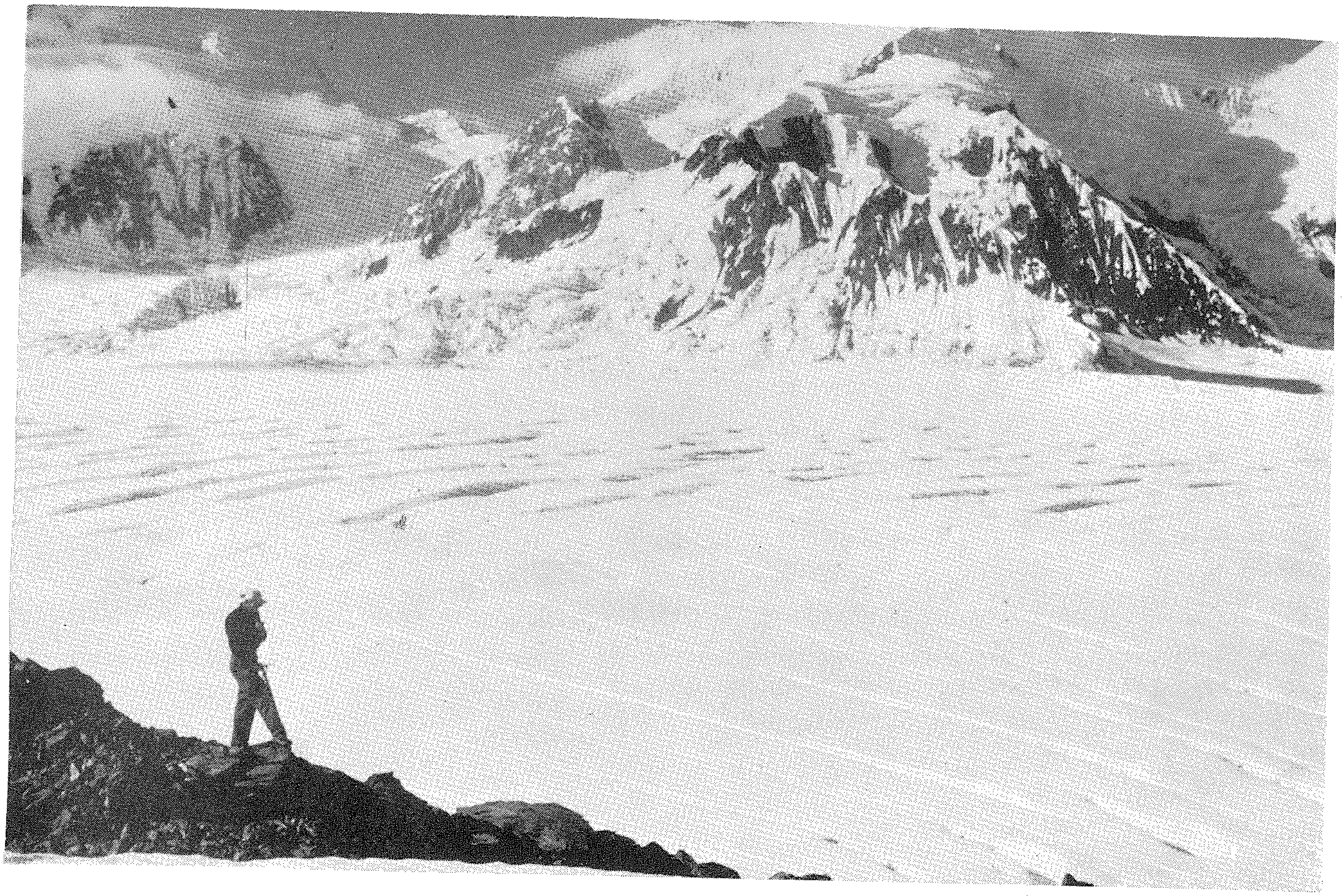
Hour	Date	Pan 3	Pan 5	Pan 6
0800-0900				
	7-24		36	14
	7-25		36	19
	7-26		15	10
	7-27		131	64
	7-28		45	16
	7-29	0	100	6
	7-30	0	70	9
	7-31	70	230	80
	8-1	0	128	33
	8-2	25	75	8
	8-3	3	85	5
0900-1000				
	7-24		35	14
	7-25		52	19
	7-26		18	10
	7-27		130	91
	7-28		240	20
	7-29	0	110	10
	7-30	0	90	12
	7-31	100	240	73
	8-1	21	116	34
	8-2	15	80	3
	8-3	28	50	7
1000-1100				
	7-24		29	14
	7-25		52	19
	7-26		90	30
	7-27		121	70

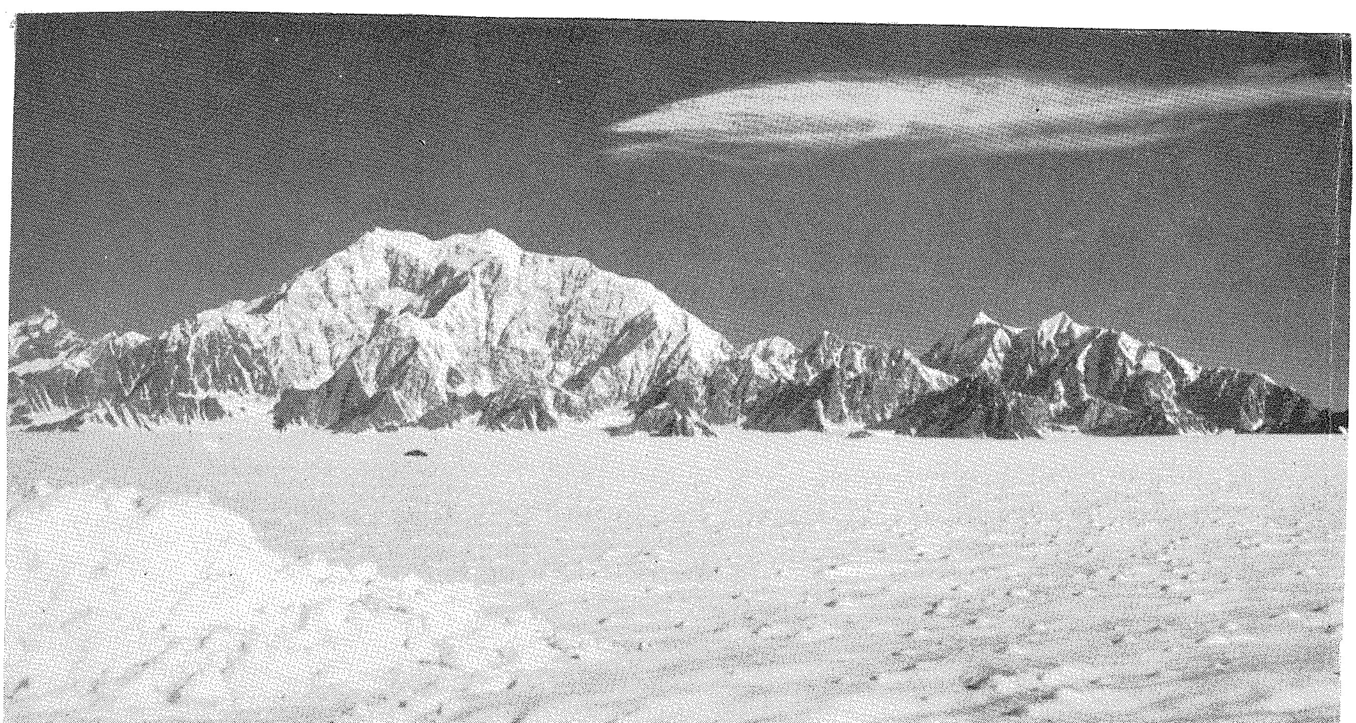
Hour	Date	Pan 3	Pan 5	Pan 6
1000-1100				
	7-28		180	22
	7-29	0	120	12
	7-30	0	140	14
	7-31	130	270	85
	8-1	60	179	55
	8-2	12	94	3
	8-3	12	66	7
1100-1200				
	7-24		29	14
	7-25		52	19
	7-26		100	35
	7-27		110	80
	7-28		150	23
	7-29	3	135	12
	7-30	2	100	18
	7-31	216	295	120
	8-1	120	248	65
	8-2	25	110	9
	8-3	9	66	6
1200-1300				
	7-24		29	14
	7-25		52	19
	7-26		128	45
	7-27		100	85
	7-28		120	13
	7-29	7	155	12
	7-30	3	92	21
	7-31	145	300	160
	8-1	208	215	48

Hour	Date	Pan 3	Pan 5	Pan 6
1200-1300				
	8-2	45	160	12
	8-3	64	125	14
1300-1400				
	7-24		29	14
	7-25		52	19
	7-26		106	50
	7-27		94	90
	7-28		105	11
	7-29	30	175	20
	7-30	4	96	24
	7-31	100	280	200
	8-1	287	285	100
	8-2	75	180	15
	8-3	50	185	10
1400-1500				
	7-24		29	14
	7-25		52	19
	7-26		55	64
	7-27		150	90
	7-28		90	11
	7-29	30	245	30
	7-30	4	305	25
	7-31	100	390	350
	8-1	287	286	110
	8-2	75	200	23
	8-3	50	90	8
1500-1600				
	7-24		29	14
	7-25		52	19
	7-26		117	53

Hour	Date	Pan 3	Pan 5	Pan 6
1500-1600				
	7-27		150	90
	7-28		90	11
	7-29	30	245	30
	7-30	4	305	25
	7-31	100	390	350
	8-1	287	286	110
	8-2	75	200	23
	8-3	50	90	8
1600-1700				
	7-24		29	14
	7-25		52	30
	7-26		175	65
	7-27		180	88
	7-28		140	10
	7-29	212	400	50
	7-30	79	250	30
	7-31	453	616	383
	8-1	375	305	140
	8-2	56	125	67
	8-3	60	50	5
1700-1800	7-24		35	3
	7-25		90	50
	7-26		200	75
	7-27		192	88
	7-28		160	20
	7-29	320	450	75
	7-30	90	255	50
	7-31	360	484	314
	8-2	157	120	157
	8-3	118	50	4

Hour	Date	Pan 3	Pan 5	Pan 6
1800-1900				
	7-24		35	3
	7-25		190	60
	7-26		210	90
	7-27		160	125
	7-28		162	22
	7-29	250	400	80
	7-30	100	275	65
	7-31	275	440	175
	8-1	350	285	100
	8-2	115	115	55
	8-3	123	49	4
1900-2000				
	7-24		35	3
	7-25		140	50
	7-26		220	120
	7-27		160	140
	7-28		164	24
	7-29	170	400	90
	7-30	125	330	80
	7-31	250	370	151
	8-1	350	293	100
	8-2	100	120	45
	8-3	100	49	2
2000-2100				
	7-24		35	2
	7-25		140	50
	7-26		190	120
	7-27		172	132
	7-28		175	25
	7-29	80	417	100





CONTENTS

LIST OF ILLUSTRATIONS

Hour	Date	Fan 3	Fan 5	Fan 6
2000-2100				
	7-30	180	350	127
	7-31	110	300	155
	8-1	350	260	80
	8-2	79	130	40
	8-3	70	49	2
2100-2200				
	7-24		35	2
	7-25		140	50
	7-26		190	120
	7-27		172	130
	7-28		164	23
	7-29	40	244	54
	7-30	180	340	127
	7-31	75	100	165
	8-1	200	200	80
	8-2	40	100	40
	8-3	30	49	2