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GLACIOLOGICAL STUDIES AT WILKES STATION,
BUDD COAST, ANTARCTICA

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

by

Richard Leo Cameron, B.Sc.

* * * * *

The Ohio State University
1963

Approved by

Richard P. Goldthwait
Adviser
Department of Geology

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INTRODUCTION

This report concerns the glaciology of the periphery of the Antarctic ice sheet in the vicinity of Wilkes Station. Wilkes Station is situated on the Budd Coast at Clark Peninsula in the northern part of the Windmill Islands, lat. $66^{\circ} 15.4'$ S, long. $110^{\circ} 31.5'$ E, Figure 1. Wilkes Station was operated by the United States from February 1957 to January 1959 as part of the International Geophysical Year Antarctic program. The active scientific disciplines were biology, seismology, aurora and air glow, geomagnetism, ionospheric physics, cosmic rays, meteorology and glaciology.

The topographically low Windmill Islands, with the Antarctic ice sheet abutting them, lie along the eastern edge of Vincennes Bay; they consist of 75 km^2 of exposed bedrock dispersed over an area of 450 km^2 . Some are true islands in Vincennes Bay but others are connected to the ice sheet by ice ramps.

The ice abuts the islands on the east and the relatively thin ice is producing a shear moraine or a Thule-Baffin type moraine, as defined by Weertman (1961, p. 965), at about 120 m elevation. The profile of the ice sheet island for 80 km to 1166 m elevation is parabolic. There

Figure 1.--Index map showing Budd Coast, Wilkes Land, Antarctica and the area of investigation.

are no crevasses along this line and there are no known nunataks inland of the Wilkes area.

To the south of the islands the Vanderford Glacier, a distinct ice stream, flows northwest and discharges in Vincennes Bay. Soundings in front of the glacier show that a deep trough extends to the north and northwest. The greatest depth is 2187 m.

From the Windmill Islands to Cape Poinsett, 150 km to the northeast, the terminus of the continental ice sheet is characterized by continuous ice cliffs and a lack of outlet glaciers or ice streams. The uniformity of morphology is due to the low relief of the subice topography.

The most impressive physical feature of Antarctica is its vast ice cover of 13.5 million square kilometers averaging 2.3 km thick (Thiel, 1962, p. 175). The amount of water stored by this ice sheet and its present mass balance, whether growing, shrinking or in equilibrium, is of utmost importance in understanding the world hydrologic cycle. Because very little was known about this ice sheet, glaciological studies of the periphery and the interior were made an integral part of the IGY program.

This is a report of one of these regime or mass balance studies of a peripheral part of the ice sheet. The aim of this glaciological work was to study the climate, the

snow accumulation and ablation, the ice and firn temperatures, and ice movement in order to ascertain the present state of the marginal ice. The condition of this ice is a reflection of the condition of the whole ice sheet.

GENERAL GEOLOGY

Geology per se was not an integral part of the IGY program, but studies were carried out on both bedrock geology and glacial geology.

The northern part of the island group has little relief and consists of gneiss, schist, pegmatite and migmatite, Figure 2. The foliation of alternating gneiss and schist and elongate bodies of pegmatite strikes east-west and has a nearly vertical dip. The southern part of the island group consists of granite and quartz diorite, which, because of weathering, has a knobby appearance, Figure 3. The maximum relief is 118 m.

The migmatite is probably an intersely metamorphosed sequence of sedimentary-volcanic rocks (Robertson, 1959, p. 17). The emplacement of the pegmatite and the granite to the south probably was contemporaneous with the metamorphism. The orogeny has been dated at 1 billion years (Cameron, Goldich, and Hoffman, 1959, p. 5). Younger basic dikes were intruded, followed by faulting.

On Clark Island, a band of manganese silicate, tephroite (Mason, 1959, p. 428), is the only indication of any economic deposit. Most other occurrences of tephroite have been in ore deposits such as at Langban, Sweden (iron-

Figure 2.--Aerial view, to the east, of Clark Peninsula, Windmill Islands. The ice sheet is in the background and Vincennes Bay in the foreground. Arrow points to Thule-Baffin moraine. Official U.S. Navy photograph.

Figure 3.--Aerial view, to the east, of Peterson Island, Windmill Islands. Note knobby topography. Official U.S. Navy photograph.

manganese), Franklin, New Jersey (zinc), and Broken Hill, Australia (lead-zinc).

Glaciation of the entire island group is shown by striae, grooves, lunoid markings, polished surfaces, erratic blocks, and ground moraine. Figure 4 shows excellent chatter marks on Bailey Island. Some polygonal patterns are formed in the ground moraine. No evidence was found that might suggest successive glaciation.

Beaches were elevated, as much as 30 m above sea level, by isotatic rebound when the area was uncovered by the retreat of the ice. Archaeolithothamnium, a coralline algae, found in a beach 23 m above sea level, has been dated by C^{14} at $6,040 \pm 250$ years BP (M-1052). This indicates that the Windmill Islands have been free of ice for at least 6,000 years. The present position of the ice sheet margin seems to be stable.

Figure 4.--Chatter marks in gneiss on Bailey Island, Windmill Islands, formed by ice movement. Mitten points in direction of ice motion.

CLIMATE

Introduction

Meteorological stations are maintained to determine the environment of a particular site and to collect data to be utilized for the interpretation of circulatory systems which ultimately provide the basis for weather forecasting. Wilkes Station, like the many other stations established on the Antarctic continent during the International Geophysical Year, maintained a meteorological program. This program was the responsibility of the U.S. Navy, but the U.S. Weather Bureau provided some assistance. However, the environment of the immediate margin and the near interior of the ice sheet was of such particular concern to the glaciological team, that two additional meteorological sites were established and maintained by the glaciologists; they were designated S-1 (8 km inland) and S-2 (80 km inland). With all three stations in operation for the greater part of an 11-month period, it has been possible to study the environment of this area.

The immediate area of Wilkes Station, which will be called Base in this report, is a combination of rock outcrops and snowdrift-ice fields at the shore of Vincennes Bay. The meteorological building was set up on a large

beach-gravel area between bedrock outcrops. In winter, snowdrifts formed around the buildings and rock outcrops and reduced the percentage of rock-to-snow-area, but at no time was all the rock covered by snow.

The Base meteorological program consisted of both surface and upper air observations, but as the glaciologist is mainly interested in surface conditions the upper air observations will not be treated here. A standard instrument shelter was located on the top of the meteorological building, at an elevation of 15 m above sea level. This housed thermometers for measuring current, maximum, and minimum temperatures and an element for continuous temperature recording. An anemometer located on the roof of the building recorded continuously both wind speed and direction. Inside the building were Speedomax recorders for the roof instruments, a mercury barometer, and a barograph. A continuous 24-hour watch was maintained with synoptic observations every 3 hours; times of beginning and ending of precipitation and obstructions to vision were also recorded. The program began on 4 March 1957 and ended on 27 January 1958, a period of 334 days. A succeeding IGY meteorological group carried on these observations until January 1959 when the management of Wilkes Station was transferred to the Australians.

The S-1 station was located on the ice sheet 8 km east-southeast of the Base, at an elevation of 262 m. In

the vicinity of S-1 the ice was intermittently covered by a thin layer of snow. The ice surface sloped $1^{\circ} 54'$ toward the west (288° True). An instrument shelter was set up, equipped with a thermometer for current temperature and a 7-day recording thermograph; no anemometer was available for this site. Observations began on 23 February 1957 and terminated on 27 January 1958. The site was visited at least once a week to change the thermograph recording paper and when field parties passed they would place time checks on the chart. Drifting snow caused the loss of records for 67 days, about 20% of the operating time. On 13 of these days, the thermograph pen arm had been held in one position by snow resulting in a featureless trace. Fifty-four days of record are missing because snow penetrated the thermograph and prevented the drum from rotating. A total of 230 days of satisfactory record were obtained.

Station S-1 was also the site for measurement of ice temperatures, discussed on page 94.

On March 11, 1957, the S-2 station was established at a site 80 km inland, at an elevation of 1166 m. This site served a dual purpose, as a meteorological station and as a location for firn studies. The surface surrounding the site was relatively flat with microrelief of only a few centimeters--there were no sastrugi. The surface sloped 40 minutes towards the west (270° True). The meteorological

equipment consisted of the instrument shelter with thermometers for measuring current, maximum, and minimum temperatures, and a 7-day thermograph. Atop a 30 m mast was a totalizing anemometer and a wind vane. Observations were three-hourly, but the 0400 hrs observation was omitted (During most of the year only three people manned this station and, because of a full scale firn study program plus maintenance and housekeeping duties, it was deemed wise for all three men to have a full night of rest). Observations began on 13 March 1957, but did not become regular until 1 May 1957; they terminated on 16 January 1958. During this time there were 282 days of observations. The succeeding IGY glaciological party did not continue the observations at S-2.

No solar radiation measurements were taken at any of the three stations.

Temperature

General

Air temperatures at the Base, at S-1, and at S-2 are influenced by the elevation of the site, condition of the surrounding surface (rock, ice or snow), altitude of the sun (time of year), cloudiness, speed and direction of the cyclonic, anticyclonic, and katabatic winds, and extent of sea ice coverage of Vincennes Bay. Although all these various factors affect the temperature regime they are not

always singular enough to be readily recognizable; although some are well defined, they all interact with one another.

The summaries of the temperature for the three stations, Base, S-1 and S-2 are presented here in Tables 1, 2, and 3.

The mean temperature of the Base for the 11-month period was -8.7°C , the coldest months were June, -17.6°C , and July, -17.5°C , and the warmest month was January with a mean of $+0.2^{\circ}\text{C}$. December was almost as warm as January with a mean of -0.1°C . The extreme maximum, $+8.3^{\circ}\text{C}$, was recorded on 20 January 1958 and the extreme minimum, -32.8°C , on 24 July 1957.

The mean temperature for the S-1 station for the period of investigation was -11.1°C , the coldest month was July with a mean of -19.8°C , and the warmest month was December with a mean of -1.8°C while January was also quite warm with a mean of -2.0°C . The extreme maximum, $+7.3^{\circ}\text{C}$, was recorded on two days, 13 and 21 December, the extreme minimum, -37.2°C , on 9 June.

The mean temperature for the S-2 station for the 11-month period was -18.8°C ; the coldest month was June with a mean of -27.6°C , and the warmest month was January with a mean of -8.8°C while December was also warm at -9.4°C . The extreme maximum, $+2.2^{\circ}\text{C}$, was recorded on 9 January 1958 and the extreme minimum, -48.2°C , on 14 June.

TABLE 1.--Summary of Temperatures at Wilkes Base (°C)

Month	Number of Days	Mean	Average Maximum	Average Minimum	Extreme Maximum	Days	Extreme Minimum	Days
Mar	28	- 4.6	- 2.4	- 7.4	+ 1.7	6, 9	-10.6	20, 28, 29
Apr	30	- 6.4	- 3.7	- 9.4	+ 2.2	4	-18.9	13
May	31	-11.8	- 7.9	-16.3	+ 5.6	31	-25.6	13, 15
Jun	30	-17.6	-14.2	-21.3	+ 1.7	24	-30.6	15
July	31	-17.5	-13.2	-22.7	- 3.9	9	-32.8	24
Aug	31	-12.5	- 8.6	-16.1	0.0	27	-23.9	9
Sep	30	-11.2	- 7.7	-14.8	- 0.6	10, 29	-22.2	1, 8
Oct	31	- 9.4	- 5.6	-13.2	+ 0.6	9	-21.7	4
Nov	30	- 4.6	- 0.9	- 8.3	+ 2.2	4, 6, 20, 27	-15.0	8
Dec	31	- 0.1	+ 3.4	- 3.6	+ 6.1	20, 21	-10.0	1
Jan	31	+ 0.2	+ 3.2	- 2.6	+ 8.3	20	- 5.6	12
Total	334	- 8.7	- 5.2	-12.3	+ 8.3		-32.8	

TABLE 2.--Summary of Temperatures at S-1 (°C)

Month	Number of Days	Mean	Average Maximum	Average Minimum	Extreme Maximum	Days	Extreme Minimum	Days
Feb	6	- 6.1	- 4.1	- 8.8	- 1.7	28	-10.9	25
Mar	22	- 5.3	-3.0	- 7.7	+ 0.6	2	-13.3	16
Apr	21	- 8.8	- 6.7	-11.6	- 1.3	4	-19.0	10
May	19	-13.6	-10.6	-17.2	- 1.1	31	-29.6	13
Jun	22	-18.8	-15.4	-21.4	- 2.9	18	-37.2	9
Jul	15	-19.8	-16.3	-23.4	-10.5	10	-30.8	7
Aug	12	-17.9	-14.7	-22.2	- 9.9	1	-28.8	10
Sept	17	-14.6	-11.4	-17.9	- 6.0	4	-24.5	8
Oct	16	-12.2	- 7.7	-17.1	-2.0	20	-22.7	28
Nov	28	- 7.6	- 2.9	-11.9	+ 6.7	20	-19.1	8
Dec	29	- 1.8	+ 2.5	- 5.7	+ 7.3	13, 21	- 9.9	8
Jan	25	- 2.0	+ 0.9	- 4.8	+ 6.0	19	- 9.3	11
12 months	230	-10.7	- 7.4	-14.2	+ 7.3		-37.2	
11 months	224	-11.1	- 7.8	-14.7	+ 7.3		-37.2	

TABLE 3.--Summary of Temperatures at S-2 (°C)

Month	Number of Days	Mean	Average Maximum	Average Minimum	Extreme Maximum	Days	Extreme Minimum	Days
Mar	12	-15.6	-11.1	-20.6	- 6.1	14	-29.0	29
Apr	9	-19.4	-17.6	-22.9	- 9.6	3	-32.3	12
May	31	-22.1	-18.0	-26.6	- 9.1	31	-39.4	21
June	30	-27.6	-24.3	-31.4	-12.7	23	-48.2	14
Jul	31	-25.7	-21.6	-30.6	-15.6	8	-44.2	23
Aug	31	-22.7	-19.5	-26.6	- 9.4	26	-34.1	19
Sep	30	-21.6	-17.6	-26.4	-10.0	11	-35.1	20
Oct	31	-19.1	-13.4	-24.8	- 6.7	2	-39.2	4
Nov	30	-14.3	- 9.7	-18.1	- 0.6	20	-23.0	13
Dec	31	- 9.4	--	-13.8	--	--	-25.1	1
Jan	16	- 8.8	- 4.0	-13.4	+ 2.2	9	-20.0	10
Total	282	-18.8	-15.7	-23.2	+ 2.2		-48.2	

Annual temperature variation

The annual temperature variation at the three stations is shown in the plot of the monthly means, Figure 5. The forms of the three curves are essentially the same. The shapes of the S-1 and Base curves differ slightly from one another mainly because of the lack of complete data from S-1. The configurations of the Base and S-2 curves are nearly identical from May until January with but one exception, July. (The temperature data from S-2 and Base was not readily comparable for March and April as there are only a total of 21 days of observations from S-2 for those two months.)

The one exception in the configuration of the Base and S-2 curves may be explained by other meteorological elements. At the Base, July temperature remained essentially the same as June, but at S-2 the July temperature rose by nearly 2°C. At the Base the mean wind speed increased from 8.9 mph in June to 10.5 mph in July, and at S-2 from 22.9 mph to 25.0 mph, an increase of 1.6 mph at the Base as opposed to 2.1 mph at S-2, an insignificant difference. Hence, wind speed, as a factor by itself, cannot be responsible for the increase in the July temperature at S-2. However, wind direction, rather than wind speed seems to be significant.

At the Base the prevailing wind was south during June and July and the mean temperature for the southerly wind

Figure 5.--Mean monthly temperatures at Base, S-1, and S-2 for the period March 1957 to January 1958.

direction remained the same for both at -19.0°C . But, for the east-southeast wind, the mean temperature increased from -19.0°C in June to -11.7°C in July. At S-2 the prevailing wind for both months was east-southeast, but there was an increase in the mean temperature from -27.5°C to -25.2°C . The mean temperature for the southerly wind at S-2 during July was -28.2°C , 3°C lower than the mean temperature with an east-southeast wind. No southerly winds were recorded during June at S-2. The mean temperature for east-southeast winds in July at both the Base and S-2 were higher than in June and the mean temperature for southerly winds during July lower than that for east-southeast winds at both S-2 and the Base. Therefore, at the Base, the temperature remained low during July, the winds being predominantly southerly, while at S-2, with dominant east-southeasterly winds, the mean temperature for July increased.

The temperature curves for these three stations typify the kernlose pattern for winter temperatures. The kernlose winter is shown where the curve of the mean monthly temperatures is quite flat and there may be one or more reversals of the expected seasonal trends (Wexler, 1958, p. 577). The curve for the mean monthly temperatures at the Base best illustrates the flat minimum although there are no reversals. The following year, 1958, had a more well-defined kernlose winter with the flat minimum and a strong

reversal occurring in July, Figure 6. The kernlose winter occurs in both the Arctic and Antarctic and is caused by cyclones initiated by baroclinic instability when the continents cool more rapidly than the oceans (Wexler, 1958, p. 593).

The average maximum and minimum temperatures for each month at the Base, at S-1, and at S-2 are given in Figures 7, 8, and 9. The temperature ranges are similar for the Base and S-1, 7.1°C and 6.9°C respectively, and at S-2 it was somewhat greater at 8.5°C .

Climate classification

At Wilkes Station the month of January 1958 had a mean temperature of $+0.2^{\circ}\text{C}$ and according to Köppen's classification of climate, areas in which the temperature of the warmest month is over 0°C and less than $+10^{\circ}\text{C}$ is classified as Tundra Climate (ET). Thus, the immediate vicinity of Wilkes Station might be so classified. However, the warmest month in some years is not above 0°C , as in 1958. The ice sheet itself is classified as EF, Frost Climate, where the mean temperature of even the warmest month remains below the freezing point.

In a recent study on the regional dynamic climatology of the Antarctic continent Sabbagh (1962) has defined specific climatic regions, Interior (I) and Marginal (M). His basis for this "regionalization" are the surface temperature

Figure 6.--Mean monthly temperatures at Wilkes Station for the period January 1958 to December 1958.

Figure 7.--Mean monthly maximum and minimum temperatures at Base for the period March 1957 to January 1958.

Figure 8.--Mean monthly maximum and minimum temperatures at S-1 for the period March 1957 to January 1958.

Figure 9.--Mean monthly maximum and minimum temperatures at S-2 for the period March 1957 to January 1958.

regimes at the US-IGY stations and the correlation coefficients between the five-day temperature trends at these stations. He gives the vicinity of Wilkes Station as eM^W--eastern Marginal Wilkes Land subregion. Sabbagh (1962, p. 97) states, however, that the subdivision of the climatic regions is subjective. Sabbagh's analysis has been confined to data from only seven Antarctic stations, over a relatively short period of time.

The year of 1957 at Wilkes was probably slightly warmer than average. The mean temperature for the period March to December at the Base was -8.9°C and would certainly have been higher if temperatures had been recorded in January and February of that year. When the expedition arrived at Wilkes on 29 January it was evident that much melting had taken place; the ice ramp contained many rivulets and in the area above the moraine were traces of many slush slides and other drainage features. Less melting occurred in the summer of 1957-1958. The years of 1958 and 1959 both had mean temperatures of -10.0°C , so 1957, with a mean of about -8.0°C , may have been an atypical year.

Lapse rate

The lapse rate over the ice sheet from Base to S-1 and to S-2 has been computed using the mean temperatures at these sites for the 11-month period March 1957 to January 1958, Table 4. Only slight differences in the lapse rates

TABLE 4.--Lapse rate at Wilkes Station

Site	Elevation (m)	Mean (°C) Temperature	Lapse Rate in °C/100 M	
			Between Adjacent Stations	Overall
Base	15	- 8.7	1.03	
S-1	262	-11.1		1.14
S-2	1166	-18.8	1.17	

are shown between the three sites. These values have been computed from data for only 11-months but the relationship remains the same even for longer periods of time. In the section on ice and firn temperatures a lapse rate between a site 96 km inland and the Base has been computed using the 10-meter temperature in the ice sheet as the mean annual temperatures. The result is a lapse rate of 1.02°C per 100 m, very similar to that computed using the meteorological data for 11-months. The lapse rate at Wilkes Station is similar to that at other locations in East Antarctica.

Temperature and wind direction

The relationship between temperature and wind direction is well defined both at the Base and at S-2. Table 5 gives the mean temperature for each wind direction for the period March 1957 to January 1958. The complete monthly tabulation is given in Appendix I.

TABLE 5.--Wind direction and mean temperature ($^{\circ}\text{C}$) at
Base and S-2

Wind Direction	N	NNE	NE	ENE	E	ESE	SE	SSE
Base Mean Temperature	7.4	9.3	8.6	7.9	7.7	7.3	8.9	9.5
S-2 Mean Temperature	22.7	29.4	16.2	18.8	17.8	18.9	20.9	23.7
Wind Direction	S	SSW	SW	WSW	W	WNW	NW	NNW
Base Mean Temperature	9.9	8.4	7.4	6.1	4.4	6.0	4.5	6.3
S-2 Mean Temperature	19.9	16.8	12.5	22.2	18.4	16.0	14.8	20.6

At the Base the lowest temperatures occurred when the wind was from the south and in general the winds from the ice sheet, to the south and east, were all cold. The southerly winds were funnelled through the depression in the ice sheet made by the Vanderford ice stream. The east-southeast winds, which came almost directly down the ice slope to the Base, were over 2.5°C warmer than the southerly winds. These east-southeast winds were katabatic and generally raised the temperature at the Base. The southerly winds, which were more frequent, were of a cyclonic nature and had a lesser force than the katabatic winds. The winds in the northwest quadrant had the highest temperatures as they were the maritime winds. The amount of fast ice in

Vincennes Bay and the pack ice beyond affected the temperature of this maritime wind so that the mean monthly temperature when winds were from this quadrant were more variable than when the winds came from the ice sheet. The relationship between wind direction and mean temperature is principally geographic--maritime versus continental. The extremes of mean temperature occur for wind directions of west (high, maritime) and south (low, continental), the difference being 5.5°C . The mean temperature of winds from north to west-southwest (maritime) was -5.8°C while the mean temperature of winds from north-northeast to southwest (continental) was -8.6°C .

Evaluation of the wind direction-mean temperature relationship at S-2 is not as straightforward as at the Base because of the predominance of wind from one quadrant and the paucity of wind from other directions. For the 11-month period only winds from east-northeast, east, east-southeast, and southeast occurred every month. The mean temperatures computed for the other directions decrease in significance as the number of months represented decreases; this varies from eight months for northwest winds to one month for north-northeast winds.

There is a significant difference between mean temperatures within the one sector in which the winds predominant. But for one exception, east, the more southerly the wind the lower the mean temperature would be. The katabatic winds

often were from the east at S-2 and as these winds warm the air the result was a slightly higher mean temperature for this wind direction. Winds from the northeast at S-2 generally represented maritime air moving in from the northern extremity of Budd Coast (about 120 km to the north) and although this air was somewhat cooled by its passage over the ice sheet it was still warmer than the air from the interior. During eight months winds were recorded from the northwest (maritime) and the mean temperature was -14.8°C . This was 1.4° warmer than the mean temperature for southeast (continental) winds.

At S-2 there is also a pronounced relationship between wind direction and mean temperature dependent upon maritime and continental air and katabatic winds.

Abrupt changes in temperature

Significant changes in temperature occurred in short periods of time associated with changes in wind direction. At the Base when the wind direction changed to south the temperature invariably dropped suddenly. However, the most spectacular changes in temperature occurred during the onset of the katabatic winds. One example is shown in Figure 10, when the temperature rose 8.9°C between 2200 hrs on 14 July and 0100 hrs on 15 July. At the same time the wind velocity increased from 0 to 40 mph. The wind continued to increase to nearly 70 mph and then it decreased rapidly. The

Figure 10.--Temperature and wind records at Base for the period 14 to 16 July 1957, showing an exceptional increase in temperature of 8.9°C in three hours coinciding with an increase in wind speed.

temperature, however, remained essentially constant after the initial increase, in spite of the variations in the wind speed.

Melting conditions

Ablation of snow and ice by summer melting and subsequent runoff is confined to a very narrow band along the coast. Melting does occur inland as far as S-2 (80 km) but here the meltwater percolates into the firn below and freezes, and material is not lost by runoff.

Two ways of comparing melting conditions at different sites, are the "melt day" and the "thawing index." The melt day is defined here as a day with a mean temperature of 0.0°C or above. The thawing index is defined as the number of days in a melt season with a mean temperature above 0.0°C multiplied by the average temperature of those days.

The following is a comparison of melt conditions at the Base and at S-1. The "melt" days and the mean temperature of those days at Base and S-1 for the period 4 March 1957 to 26 January 1958 are given in Table 6. There were 36 days at the Base with a mean temperature of $+0.7^{\circ}\text{C}$ and seven days at S-1 with a mean temperature of $+0.4^{\circ}\text{C}$. There five times as many "melt" days at the Base and the thawing index at the Base was nine times that of S-1.

TABLE 6.--Melt days at Base and S-1

Date		Mean Temperature (+°C)	
		Base	S-1
May	31	0.3	--
Dec	9	0.0	
	10	1.1	
	12	0.1	
	13	0.3	0.0
	14	0.1	
	15	0.8	
	16	0.1	0.0
	17	1.5	
	18	2.0	
	19	2.0	
	20	1.5	
	21	1.4	
	22	0.0	
	24	0.0	
	26	1.1	
	29	0.0	
	30	0.5	0.8
	31	0.4	
Jan	1	0.0	
	3	0.0	
	4	0.8	
	5	2.3	
	6	1.4	1.1
	7	1.1	0.7
	8	0.5	
	9	0.3	
	16	0.1	
	17	1.1	
	18	0.1	
	19	--	0.2
	20	2.8	
	22	0.0	
	23	0.3	
	24	1.2	0.1
	25	0.3	
	26	1.1	
Total No. of Days	37	36	7
Average Temperature		0.7	0.4

	<u>Melt Days</u>	<u>Thawing Index</u>
Base	36	25.2
S-1	7	2.8

Actual ablation measurements at S-1, Stake #410, and at Base, Stake #430, for the period 25 November 1957 to 23 January 1958 showed a loss of 10 cm of snow at S-1 compared to 41 cm of snow at Base. There was four times as much ablation at Base than at S-1.

Melt days and the thawing index do not represent the exact number of hours available for melting but rather are a measure of the difference in magnitude of the ablation at different sites.

Plotting melt days and thawing index against elevation in Figure 11 and extrapolating, there would be no melt days above 310 m elevation and above 300 m the thawing index would be zero. This indicates that the upper limit of intense melting should be at or below 300 m elevation.

Pressure

The annual variation of pressure for the 11-month period shows two maxima of similar magnitude, one in June and the other in December, and a minimum occurring in September, Figure 12. The pressure variation at Mirny was identical with that at Wilkes and the variation at Halley Bay, on the other side of Antarctica, also exhibited two maxima and a deep minimum in September (MacDowall, 1959, p. 423). The average pressure at Wilkes was 987.00 mb, the

Figure 11.--Melt days and thawing index versus elevation.

Figure 12.--Mean monthly atmospheric pressure at Wilkes Station during the period March 1957 to January 1958.

extreme maximum 1091.1 mb occurred on 23 May 1957 and the extreme minimum 951.3 mb on 10 September 1957.

Months with low pressure were months with high winds and months with high pressure had light winds.

Pressure jumps occurred at the onset of katabatic winds and the pressure remained low until the winds ceased. Figure 13 shows the barograph trace at the Base for the period 17 April to 21 April and Figure 14 shows the wind record trace for the period 0500 to 0900 hrs on 18 April. These figures show the relationship between pressure and katabatic winds. Figure 15 shows the barograph trace for the period 25 May to 29 May. Note the significant pressure jumps on the 28th caused by gusty katabatic winds.

Wind

General

Wind at the Base was highly variable in direction but was predominantly southerly. High winds, east-southeast, came sweeping down from the ice sheet and light winds blew in from Vincennes Bay in the northwest quadrant. The mean wind speed for the 11-month period was 11.7 mph; the mean monthly wind speeds ranged from 7.2 mph in December to 18.1 mph in September. The highest hourly wind speed, 76 mph, an east wind, was recorded in May and the highest gust, 105 mph, was recorded on 30 September.

The wind direction at S-2 was less variable, with over 43% of observations of the wind directions being

Figure 13.--Barograph trace from Wilkes Station for the period 17 April to 21 April 1957. The sudden pressure drop coincides with the onset of katabatic winds, Figure 14.

Figure 14.--Record of wind direction and speed at Wilkes Station for the period 0500 to 0900 hours on 18 April. The top trace is wind direction, the bottom trace speed. This record shows the onset of katabatic winds.

Figure 15.--Barograph trace from Wilkes Station for the period 25 May to 29 May 1957. The pressure jumps on 28 May resulted from gusty katabatic winds.

recorded as east-southeast. At S-2 an essentially smooth ice sheet slopes 40 minutes up towards the inland in an east-southeasterly direction, so that there are no local topographic prominences to effect wind directions and speeds. The mean wind speed at S-2 was 26.0 mph; the mean monthly wind speeds ranged from 19.0 mph in March to 32.9 mph in December. At S-2 the highest three-hourly wind speed was 78 mph recorded in December and the highest wind speed recorded was 84 mph for a three-minute interval on 18 December. Wind speed in gusts were not recorded.

The monthly mean wind speeds for the Base and S-2 are given in Table 7 and are compared graphically in Figure 16. The curves for wind speed have essentially the same configuration, suggesting that the Base and S-2 have similar variations in their wind regimes. The curves, however, have a difference in mean wind speed of 14 mph.

In reviewing the monthly mean wind speeds it is discovered that September was the month with the highest mean wind speed at both the Base and S-2; the mean wind speed at the Base decreased steadily from September to December; at S-2 there was a decrease from September to October; in November the wind speed remained essentially the same as in October and in December it increased to about the same high value as in September. The steady decrease of mean wind speeds at the Base as summer approached is a characteristic feature of Antarctic coastal stations, caused by the influx

TABLE 7.--Wind at Wilkes Base and S-2, Predominant Direction, Mean Monthly Speed, and Highest Hourly Speed

Month	Dominant Direction	Base		Dominant Direction	S-2	
		Mean Monthly Speed (mph)	Highest Hourly Speed (mph)		Mean Monthly Speed (mph)	Highest Hourly Speed (mph)
Mar	S	11.3	52.0	E	19.0	50.0
Apr	S	15.5	71.0	ESE	28.4	57.0
May	S	13.8	76.0	SE	26.2	57.0
Jun	S	8.9	47.0	ESE	22.9	46.0
Jul	S	10.5	71.0	ESE	25.0	61.0
Aug	S	14.8	66.0	ESE	30.4	62.0
Sep	E	18.1	67.0	ESE	32.4	68.0
Oct	ESE	11.7	58.0	ESE	24.1	54.0
Nov	NE	8.4	40.0	ESE	23.9	48.0
Dec	NE	7.2	46.0	E-ESE	32.9	78.0
Jan	NE	8.3	48.0	E	20.0	47.0

of maritime air along the coast which prevents anticyclonic and katabatic winds from reaching the coastline.

The one major anomaly of these wind regimes occurred in the month of December. The high mean wind speed for S-2 during the month of December was caused by an extremely violent storm that lasted three full days. The wind began to increase shortly after 0100 hours on the 17th and persisted until about midnight on the 19th; a calm was recorded at 0100 hrs on the 20th. The wind speeds for the period

Figure 16.--Mean monthly wind speed at Base and S-2 for the period March 1957 to January 1958. The mean wind at S-2 was 14 mph greater than at Base.

are given in Table 8 and plotted in Figure 17. The highest three-hourly wind speed recorded during this storm was 78 mph on the 18th. The following mean wind speeds calculated for various portions of this storm show the persistence and severity of the storm. This storm, with its east and east-southeast winds, affected mainly the S-2 site. During the same period at the Base wind direction and speeds were variable; however, there were occasional high winds (35 mph) from the ice sheet. These outbursts of high winds occurred on all three days but the winds were not persistent.

TABLE 8.--Mean Wind Speeds at S-2 for Intervals During the Period 0100 Hours on 17 December to 0100 Hours on 20 December 1957

Interval	Number of Hours	Mean Wind Speed
17 Dec 0100 - 2200	21	48
18 Dec 0100 - 2200 hrs	21	62
19 Dec 0100 - 2200 hrs	21	40
17 Dec 0100 - 19 Dec 0700 hrs	54	55
17 Dec 0100 - 20 Dec 0100 hrs	72	49

Figure 17.--Wind speed recorded at S-2 for the period 0100 hours 17 December to 0100 hours 20 December.

Wind direction: frequency
and speed

The percentage frequency of the different wind directions for each month at both sites is given in Appendix I and is shown as wind roses in Figure 18. These wind roses also show the mean wind speed for each direction. The wind direction frequency and mean wind speed are summarized in Figure 19 and Table 9.

TABLE 9.--Wind Direction and Mean Wind Speed (mph), at
Wilkes Base and S-2

Wind Direction	N	NNE	NE	ENE	E	ESE	SE	SSE
Base Wind Speed	7.8	8.0	9.3	12.2	20.3	29.2	7.6	8.8
S-2 Wind Speed	7.9	3.0	12.3	19.0	32.7	30.1	21.1	14.5

Wind Direction	S	SSW	SW	WSW	W	WNW	NW	NNW
Base Wind Speed	6.3	8.7	6.1	5.5	4.9	5.5	7.8	6.7
S-2 Wind Speed	6.3	7.2	6.1	10.5	7.9	6.0	7.4	5.8

At the Base the winds were predominantly from the northeast and southwest quadrants with the predominant wind being southerly throughout most of the period. The strongest winds were east and east-southeasterly. The most variable winds occurred during the period October to January. December was the month with the lightest winds and June had

Figure 18. Wind roses, frequency and speed, for Base and S-2 for the period March 1957 to January 1958.

Figure 19.--Wind rose, average frequency and average speed, for Base and S-2 for the period March 1957 to January 1958.

the highest percentage of calm, 25%. Calm was recorded each month at the base and ranged between 5% and 25% of the observations and averaged 15%.

At S-2 the winds were nearly all from the southeast quadrant with east-southeast being the dominant direction and having the highest mean wind speed. Month to month variations were only slight. March had considerable wind from the northwest and northeast quadrants and the highest mean speed was from the east-northeast; March also was the month with the highest percentage of calm, 5%. Other months with calm were June 1%, July 1%, and September 2%. For the entire period the percentage of calm at S-2 was 1%. The month of October had the most variable winds.

Katabatic winds

The katabatic winds which occur at the Base and at S-2 are caused by the cooling of the surface of the inland ice and the subsequent gravitational movement of this air. These outbreaks of surface air can occur diurnally due to nocturnal cooling in spring and autumn and any time in winter by the continual cooling effect. The summer months have less frequent katabatic flow and the winter months the most frequent. The triggering of the winter katabatic is directly related to the offshore movement of low pressure systems and generally begin just as the low has passed, i.e., the cyclonic winds are blowing downslope and thus encourage the gravity winds to develop.

The katabatic winds were characterized by their abrupt beginning and an extreme gustiness in the first few hours. These winds generally produced a foehn effect, raising the temperature rapidly in only a few hours and the pressure always dropped quickly when the high winds began. The temperature rise was due to the adiabatic warming of descending air. The katabatic flow was frequently active on the ice sheet above an elevation of 400 m while it was calm at the Base.

Drifting and blowing snow

Snow is moved about on the ice sheet by winds and this eolian action produces many microrelief features such as sastrugi, barchans, ripple marks, and various irregular features. The wind produces both depositional and erosional features. The snow movement on the ice sheet is called snow drift and blowing snow. Snow drift is the term used for snow which is moved along the surface and up to a height of 2 meters. Snow drift interferes with some work and poor visibility at the upper limit, 2 m, can restrict movement of a man on foot or skis, but vehicles can usually travel during snow drift conditions. Blowing snow describes the condition when the snow is carried high into the air. The blowing snow can reach heights of well over 50 meters and can blot out the sun completely and reduce horizontal visibility to less than 30 m.

At S-2 snow drift generally began when the wind speed reached 20 mph; however, drift was recorded with winds as low as 15 mph and as high as 40 mph. Blowing snow usually began at 35 mph but did begin as low as 30 mph. The lower limits of wind speed for drifting and blowing snow depend on the condition of the surface snow. Immediately after a snowfall drift can begin with only a light wind. At high wind speeds snow drift without blowing snow can occur because of either a very cohesive surface or the depletion of the snow supply. Observations at S-2 have shown that although the wind speed may remain constant the amount of snow being carried in the air decreases as the storm continues. The density of the drifting and blowing snow at any given time depends on the amount of snow which was available before the storm began and the elapsed time since the onset.

Much of this drifting and blowing snow is merely transported from one area to another but along the coastal ice slopes this snow is blown off the ice sheet into the sea. Hobbs (1926, p. 34) has envisioned the winds as a "centrifugal snow broom."

The blowing snow frequently thwarted attempts to reach the S-2 station from Base. The winds on the ice sheet would swirl the snow into the air and make the visibility practically zero. Occasionally a large eddy within this blowing snow would pass by and in the center

there would be no blowing snow and perfect visibility. The winter darkness was found to be the best time to make the trip from the Base to S-2 for even if the blowing snow did occur the vehicle drivers could follow the old tracks in the snow which were clearly illuminated by the headlights.

Cyclonic Circulation

Synoptic data from weather stations in Antarctica have been analyzed by Rastorguev and Alvarez (1958); by Alt, Astapenko, and Ropar (1959); and by Astapenko (1959); and they have formulated the general pattern of atmospheric circulation for Antarctica. The trajectories of the depressions are both latitudinal and meridional; the cyclonic activity over the continent is weaker in winter than any other season; cyclones frequently cross the continent from the Ross to the Weddell Sea, and in East Antarctica there is a quasi-stationary anticyclone.

Meridional depressions intersect the Antarctic coastline to the east and west of the Budd Coast area (Astapenko, 1959, p. 249) and are not a major factor in the weather at Wilkes Station. The latitudinal depressions do affect Wilkes and are usually movements of the stationary depression which lies between Wilkes Station and the Oasis Station to the west. These depressions which move eastward along the periphery of the continent are generally located on a trajectory to the north of Wilkes Station. Astapenko (1959,

p. 252) notes several areas of outflow and inflow of air along the periphery of Antarctica and the Budd Coast is not one of these areas. The Budd Coast is a unique part of the coastline of East Antarctica: it is affected only by the latitudinal trajectory depressions, so that there is no great inflow or outflow of air and a quasi-stationary anticyclonic area is located inland.

Precipitation

Precipitation observations in the Antarctic are still relatively scarce and those that do exist are of questionable value. The main difficulty is in distinguishing between falling and drifting snow. When there are only light winds and snow is in the air, then it is almost without doubt snowfall. With high storm winds, snow is gathered from the surface and into the air and this makes positive determination of snowfall nearly impossible. Determination of whether snow is being precipitated in the midst of a storm with high winds can be made by exposing a glass plate prepared with a solution of formvar and ethylene dichloride and collecting the snow crystals. These crystals can then be examined to determine if any new snow is present. Honkala (1958, p. 3) has shown the feasibility of this method.

Drifting and blowing snow enter snow gauges and thus Antarctic snow gauge data are never used as absolute precipitation values. The high winds may cause the snow to

by-pass the gauge whereas the greater amount of snow in the air may tend to increase the amount of snow which would ordinarily enter the gauge. The magnitude of these effects at Wilkes is not known.

The precipitation at Wilkes Station and at S-2 was always in the form of snow with one exception. Rain fell at the Base on 18 and 19 April, 1957, for a total period of 16 hours.

The precipitation gauge at the Base recorded an amount of 370 mm of water for the 11-month period. The monthly increments of this "precipitation" are plotted in Figure 20. No snow gauge was operated at S-2. However, accumulation of snow in that area amounted to 62 mm of water. This is the average accumulation at ten stakes for the period 20 March 1957 to 18 January 1958. Of the precipitation at any site on the ice sheet some remains as net accumulation and the remainder is lost by wind transport and sublimation. Thus the 62 mm of accumulation at S-2 is a net value after considering incoming precipitation and drift and outgoing drift and sublimation.

The number of days with precipitation at the Base and at S-2 are given in Table 10; of 334 days of observations at the Base there were 182 days with precipitation or 54%, and at S-2 of 282 days of observations there were 92 days with precipitation, or 33%.

Figure 20.--Mean monthly precipitation at Wilkes Station for the period March 1957 to January 1958.

TABLE 10.--Number of Days with Precipitation at Wilkes Base and S-2

Station	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Total
Base	24	23	17	11	18	20	20	11	16	12	11	182
S-2	(6)	(4)	7	4	13	7	11	16	10	7	(7)	92

() not a full month of observations.

Conclusions

The climate of the Wilkes area is quite distinctive. At the Base the mean annual air temperature of -9.4°C for the six year period 1957-1962 (unpublished data, U.S. Weather Bureau) is at least 1°C higher than at any other coastal station in East Antarctica.

Persistent anticyclonic winds from the ice sheet and the passage of low pressure centers to the north of the area both tend to maintain continental conditions on the ice sheet nearly to the coast. Thus the ice sheet area inland from Wilkes Station receives little precipitation from cyclones and there is low snow accumulation.

ACCUMULATION OF SNOW

Introduction

At the beginning of the IQY very little was known about the amount of snow accumulating over the Antarctic ice sheet. Some studies had been made by Schytt and Swithinbank at Maudheim and by Wade at Little America. Therefore measurement of accumulation was one of the important aspects of the glaciological program.

Nearly all of the Antarctic ice sheet lies within the zone of accumulating snow. Some net ablation occurs around the periphery of the continent, mainly in East Antarctica, but the area over which such ablation occurs is less than one-half of one per cent of the entire ice sheet. At Wilkes Station the ablation zone reaches to an elevation of about 225 m and above this snow is accumulating year after year.

The amount of snow accumulating in the study area was measured both by stakes and by stratigraphic techniques in several shallow pits and one deep excavation.

Stake Measurements

Snow Density

The water equivalent of snow accumulation recorded at stakes along the Sullivan and S-2 Trails and at S-2 has been determined using a snow density of 0.37 gm cm^{-3} . This value has been derived from measurements made by Cameron in 1957 and Hollin (1961, p. 183) in 1958. These determinations are given below in Table 11.

Sullivan Trail

On 8 February 1957 a short reconnaissance trip was made onto the ice sheet and a course was followed due east for 40 km and then east-southeast for 1.5 km. A series of stakes was emplaced for measurement of snow accumulation and they were remeasured on 19 November 1957.

The accumulation along this trail for the 284 day period is shown in gm cm^{-3} in Table 12. The accumulation was irregular from Stake #2 at 345 m elevation to Stake #12 at 711 m elevation and no trend related to elevation or distance from the coast is exhibited. No snow accumulated at Stake #3. The average accumulation at all 11 stakes, based on a snow density of 0.37 gm cm^{-3} , was 11.1 gm cm^{-2} water. However, this value must be treated with caution because large seasonal variations in accumulation may occur and the standard deviation of the observations is large (5.0 gm cm^{-2}) compared with the mean. Extending this rate

TABLE 11.--Density Measurements of Surface Snow

Date	Depth (cm)	Density (gm cm ⁻³)	
15 November 1957	3	0.39	
	11	0.40	
	16	0.35	
	19	0.35	<u>0.37</u>
6 August 1958	0-18	0.38	<u>0.38</u>
	3	0.33	
	8	0.37	
	14	0.36	
	19	0.32	
	23	0.30	<u>0.34</u>
	3	0.31	
	9.5	0.36	
	15	0.31	
	21	0.30	
	25	0.41	
	28	0.43	<u>0.35</u>
8 August 1958	3	0.36	
	9	0.36	
	14.5	0.38	
	20.0	0.32	
	25.5	0.34	<u>0.35</u>
	3	0.41	
	8	0.38	
	13	0.35	<u>0.38</u>
	3	0.40	
	8.5	0.40	
	10.5	0.38	
	14.0	0.39	<u>0.39</u>
13 September 1958	4	0.38	
	10	0.40	
	15	0.37	
	21	0.37	
	27	0.34	
	31	0.36	<u>0.37</u>
	4	0.35	
	10	0.33	
	15	0.37	
	20	0.31	
	24	0.32	
	29	0.35	<u>0.34</u>

to cover one year, gives an annual accumulation of
14.3 gm cm⁻².

TABLE 12.--Snow Accumulation on Sullivan Trail, 4 February
1957 to 19 November 1957

Trail Distance from Wilkes Station (km)	Stake Number	Approximate Elevation (m)	Accumulation	
			Snow (cm)	gm cm ⁻²
12.8	2	345	18.0	6.7
16.1	3	412	0.0	0.0
19.3	4	455	32.5	12.0
22.5	5	485	40.5	14.9
25.7	6	525	16.0	5.9
28.9	7	566	24.0	8.9
32.2	8	604	27.0	9.9
35.4	9	641	52.0	19.2
38.6	10	668	28.0	10.4
40.2	11	691	40.0	14.8
41.8	12	711	52.0	19.2
Average			30.0	11.1

S-2 Trail

Eight accumulation poles were set out along the trail from S-2 to Wilkes Station on 18 October 1957. Accumulation was measured periodically during the remainder of 1957 and throughout 1958. The last measurements were made on 17 October 1959.

The cumulative curves of accumulation at each stake are given in Figure 21. The curves differ from one another in detail but they all record nearly the same general pattern of ablation and accumulation. From October 1957 to March of 1958 ablation of about 5 gm cm^{-2} occurred at all stakes except No. 8 where there was neither net gain nor loss. The major amount of snow accumulated between March and September 1958, about $10\text{-}15 \text{ gm cm}^{-2}$ gross accumulation. Between October 1958 and October 1959 the accumulation was in the order of 5 gm cm^{-2} net accumulation. The net accumulation for each stake for the entire period is plotted in Figure 22 and the data for each stake for the entire period is given in Appendix II. The net accumulation for these stakes is given in Table 13.

The accumulation along the S-2 trail from Stake No. 8 to 467 m elevation to Stake No. 1 at 1091 m elevation is irregular and not clearly affected by elevation or distance from the coast. There is slightly higher accumulation at Stakes No. 6 and No. 8 which are nearest the coast but the difference between the accumulation at these stakes and the others is too small to be significant. The average annual accumulation along the trail is 7.9 gm cm^{-2} .

Figure 21.--Snow accumulation (gm cm⁻²) at S-2 Trail stakes, cumulative and mean accumulation, for the period October 1957 to October 1959.

NET ACCUMULATION ALONG S-2 TRAIL
18 OCT. 1957 TO 17 OCT. 1959

Figure 22.--Net snow accumulation (gm cm^{-2}) at S-2 Trail stakes for the period October 1957 to October 1959.

TABLE 13.--Snow Accumulation on the S-2 Trail, 18 October 1957 to 17 October 1959

Trail Distance from Wilkes Station (km)	Stake Num- ber	Eleva- tion (m)	Accumulation (2 years) gm cm ⁻²	Annual Average Accumulation gm cm ⁻²
17.0	8	467	17.9	9.0
25.3	7	574	16.5	8.3
33.5	6	673	18.0	9.0
41.4	5	772	13.1	6.6
49.5	4	861	16.9	8.5
57.6	3	944	15.5	7.9
65.6	2	1016	16.2	8.1
73.6	1	1091	12.2	6.1
Average			15.8	7.9

S-2 accumulation--
movement stakes

On 20 March 1957 a set of 12 bamboo poles was implanted in the vicinity of S-2 (1166 m elevation) in a geometric pattern covering an area of about 27 sq. km. The poles were given letter designation A to L. The poles were measured periodically until 10-17 January 1959.¹ The accumulation at each stake for the 668 day period is detailed in a data table in Appendix II and cumulative curves of accumulation at each stake and the curve of the average accumulation for

¹A will not be considered here as a complete set of readings was not taken.

all 11 stakes appear in Figure 23. The net accumulation at this set of stakes is given in Table 14. The accumulative curves for each stake are in general similar and most exhibit ablation in December 1957 - January 1958. The lesser variability of these data compared with the Sullivan Trail results is due primarily to the greatly increased period of the observations. The average accumulation at these stakes was 23.6 gm cm^{-2} for the 668 day period; this is an annual accumulation of 12.9 gm cm^{-2} .

TABLE 14.--Snow Accumulation at S-2 Movement Stakes, 20 March 1957 to 10-17 January 1959

Stake	Accumulation 668 days gm cm^{-2}	Average Annual Accumulation gm cm^{-2}
B	24.8	13.6
C	29.6	16.2
D	10.7	5.8
E	25.9	14.2
F	24.4	13.3
G	14.4	7.9
H	29.6	16.2
I	28.9	15.8
J	19.6	10.7
K	24.4	13.3
L	27.7	15.1
Average	23.6	12.9

Figure 23.--Snow accumulation (gm cm⁻²) at S-2 movement stakes, cumulative and mean accumulation, for the period March 1957 to 10-17 January 1959.

S-2 Weather Bureau stakes

Three wooden stakes were set in the snow as a group upwind from the S-2 station on 13 March 1957. They were read periodically until the 16 October 1959. The snow accumulation data for these stakes are in Appendix II and a curve of average accumulation at the three stakes appear in Figure 24. This curve clearly shows the deflation during the summer months of 1957-1958. The average accumulation for the 918 day period was 39.9 gm cm^{-2} or an annual average accumulation of 15.9 gm cm^{-2} .

Variation of annual accumulation

The accumulation of snow at stakes in the Wilkes area is irregular, exhibiting sudden increases and decreases in net accumulation. When any one year increment of a curve is compared with another yearly increment on the same curve (may be overlapping) the difference can be quite pronounced. The average annual accumulation on the S-2 trail for the period of measurement was 7.9 gm cm^{-2} , but when different yearly intervals within the period of measurement are used quite different values are obtained.

<u>Year</u>	<u>S-2 Trail</u> Accumulation Annual gm cm^{-2}
2 Jan 1958 - 7 Jan 1959	11.9
22 Jan 1958 -17 Jan 1959	12.9

Figure 24.--Mean snow accumulation (gm cm^{-2}) at U.S. Weather Bureau stakes at S-2, for the period March 1957 to October 1958.

The average annual accumulation as recorded at the S-2 accumulation-movement stakes was 12.9 gm cm^{-2} . Using different yearly increments within the period of measurement the following values are obtained:

S-2 Accumulation-Movement Stakes

<u>Year</u>	<u>Annual Accumulation</u> <u>gm cm^{-2}</u>
18 Jun 1957 - 20 May-June 1958	7.3
18 Jan 1958 - 10-17 Jan 1959	17.9

The average annual accumulation recorded at the Weather Bureau stakes was 15.9 gm cm^{-2} . Yearly increments are listed below.

Weather Bureau Stakes

<u>Year</u>	<u>Annual Accumulation</u> <u>gm cm^{-2}</u>
11 April 1957 - 1 Apr 1958	12.7
7 May 1957 - 7 May 1958	17.3
7 Aug 1957 - 4 Aug 1958	22.7
4 Sep 1957 - 3 Sep 1958	23.5
11 Nov 1957 - 16 Nov 1958	20.9
2 Jan 1958 - 8 Jan 1959	22.4

These figures from the three sets of stakes show that the accumulation of snow in the Wilkes area is irregular in time. By comparison, the cumulative curve of snow accumulation of Maudheim is relatively smooth so that overlapping yearly intervals of annual accumulation show little difference in values (Schytt (1958, p. 165).

This irregular accumulation at Wilkes is probably due to a combination of low, infrequent precipitation and the erosion of the snow surface by storm winds.

Summary

The annual accumulation along the Sullivan trail was 14.3 gm cm^{-2} ; for the S-2 Trail it was 7.9 gm cm^{-2} , at the S-2 accumulation-movement stakes 12.9 gm cm^{-2} and at the S-2 Weather Bureau stakes, 15.9 gm cm^{-2} . Figure 25 shows the average cumulative curves for the accumulation S-2 trail, S-2 accumulation-movement stake, and Weather Bureau stakes.

Pit Studies

General

Accumulation stakes were used to measure the amount of new snow being deposited in the area and as a supplement to these measurements a series of shallow pits and one deep pit were made to study earlier accumulation.

The determination of snow accumulation by stratigraphic techniques has been successfully demonstrated by Ahlmann (1936), Schytt (1955, 1958), and Benson (1962). In their work on glaciers of the North Atlantic coasts, Greenland and at Maudheim in Antarctica, they dealt with areas of relatively high accumulation and where the seasonal variations of grain size, density, and hardness were pronounced.

Figure 25.--Cumulative snow accumulation (gm cm^{-2}) at S-2 Trail stakes, S-2 movement stakes, and U.S. Weather Bureau stakes at S-2.

Most of Antarctica, however, is an area of low accumulation and low temperature, where seasonal variations are not great and where constant high winds corrode the surface. The dissimilarity of environment of glaciers of the northern hemisphere and the interior of the Antarctic has been of prime concern to glaciologists since 1957. The major difficulty inland has been the stratigraphic identification of annual layers in regions where there is no melting and the surficial microrelief is of the same order as or greater than the annual accumulation.

In the Wilkes area summer melting occurs so that annual crusts of thin ice layers and crystal aggregates are formed. In such conditions, the study of snow stratigraphy revealed in pit walls allows a reliable determination of annual accumulation.

Shallow pits

During 1957 a series of eight pits one to two meters deep were made; six along the S-2 trail, one 16 km east-southeast of S-2, and one at the end of the Sullivan Trail. Density, ramm hardness, stratigraphy and grain size were recorded. The pit diagrams including all of the data appear in a data report (Cameron, Løken and Molholm, 1959).

The summer horizons in these pits have been identified by the combination of melt crusts between one and 5 mm thick and an overlying layer of loose, coarse-grained

(1-3 mm) firn typical of fall snow. In some instances sublimation crystals as large as 4.0 mm were observed above the melt crusts. The winter snow was hard-packed, fine-grained firn of less than 0.5 mm in diameter.

The summer horizon or melt layers probably occur in January of each year.

The summer horizons have been identified for the pits and the water equivalent of the snow accumulation has been computed using the average of the firn density between summer horizons.

SHALLOW PITS

<u>Date</u>	<u>Location</u>	<u>Summer Horizon depth (cm)</u>	<u>Accumulation Snow (cm) gm cm⁻²</u>	
9 Feb 1957	Sullivan Trail	7	43	18.1
		50	48	20.8
		98	24	10.4
		122	36	15.1
		158	30	11.6
		188		
		Average	36.2	15.2
9 Dec 1957	10 mi ESE of S-2	12	18	6.8
		30	27	11.7
		57	23	10.5
		80		
		Average	22.7	9.7
25 Nov 1957	S-2 Trail, Pit at Flag #1	27	14	5.3
		41	19	8.7
		60	15	7.0
		75	30	13.7
		105		
		Average	19.5	8.8

SHALLOW PITS--continued				
<u>Date</u>	<u>Location</u>	<u>Summer Horizon depth (cm)</u>	<u>Accumulation Snow (cm) gm cm-2</u>	
28 Nov 1957	S-2 Trail, Pit at Flag #2	38	17	7.4
		35	26	10.7
		81	37	16.7
		118	29	12.9
		147	16	6.4
		163	16	6.4
		179		
		Average	23.5	10.1
30 Nov 1957	S-2 Trail, Pit at Flag #3	14	12	4.7
		26	12	5.2
		38	27	12.6
		65	21	9.2
		86		
		Average	18	7.9
30 Nov 1957	S-2 Trail, Pit at Flag #4	12	25	9.4
		37	16	6.0
		53	33	14.0
		86	22	9.5
		108	26	11.1
		134	29	12.3
		Average	25.2	10.4
1 Dec 1957	S-2 Trail, Pit at Flag #5	25	25.0	10.0
		50		
		Average	25.0	10.0
	S-2 Trail, Pit at Flag #6	24	31	13.3
		55	18	7.7
		73		
		Average	24.5	10.5

A summary of the accumulation determined from the shallow pit studies is given in Table 15. The accumulations for the S-2 trail and the site 16 km east-southeast of S-2 are all of the same order of magnitude, while the accumulation at the end of the Sullivan trail is somewhat higher. The four accumulation years 1953-1956 inclusive are common to the pits at Sullivan Trail and S-2 Trail

TABLE 15.--Accumulation determined from Shallow Pits

Year	Sullivan Trail	16 Km ESE of S-2	Accumulation - gm cm ⁻²					
			S-2 Trail Flag					
			#1	#2	#3	#4	#5	#6
1956	18.1	6.8	5.3	7.4	4.7	9.4	10.0	13.3
1955	20.8	11.7	8.7	10.7	5.2	6.0		7.7
1954	10.4	10.5	7.0	16.7	12.6	14.0		
1953	15.1		13.7	12.8	9.2	9.5		
1952	11.6			6.4		11.1		
1951				6.4		12.3		
Average	15.2	9.7	8.8	10.1	7.9	10.4	10.0	10.5

flags 1, 2, 3, 4. The average accumulations for these years are given below.

Site	Accumulation gm cm ⁻²
Sullivan Trail Pit	16.1
Flag #1	9.7
#2	7.9
#3	11.9
#4	8.7

The average annual accumulation at Stake #12 near the pit on the Sullivan Trail is extrapolated to be 24 gm cm⁻². The average accumulation by states measurements at Flags 1-4 is 7.6 gm cm⁻² and the above pit measurements give an average of 9.5 gm cm⁻². Thus the same relationship between

the accumulation along the S-2 trail (low) and the end of the Sullivan Trail (high) is shown both by stakes and by pit studies.

There is no definite pattern of low and high accumulations for the years 1953 to 1956. There is, however, a slight indication of such a variation in comparing the pits at S-2 Trail Flags #2 and #3.

<u>Year</u>	<u>Accumulation (gm cm⁻²)</u>		<u>Average</u>
	<u>Flag</u> <u>#2</u>	<u>#3</u>	
1956	7.4	4.7	6.0
1955	10.7	5.2	8.0
1954	16.7	12.6	14.6
1953	12.9	9.2	11.0

¹⁸O/¹⁶O study at S-2

The oxygen-isotope method of differentiating between winter and summer snow is based on a decrease of the ¹⁸O/¹⁶O ratio with decreasing temperature of precipitation (Sharp and Epstein, 1962, p. 274). In January 1959 Hollin excavated a pit 140 cm deep at S-2 (Hollin, et al., 1961, pp. 192-193), analysis. Sharp and Epstein (1962, pp. 273-285) have analyzed the samples and the plot of these data and the stratigraphic interpretation (by Hollin) appear in Figure 26 (their Figure 5).

Figure 26.--Oxygen-isotope ratios in shallow pit at S-2. From Sharp and Epstein (1962); their Figure 5.

Although there is a summer peak recorded by $\delta^{18}\text{O}/\delta^{16}\text{O}$ at 33 cm that is not indicated in the stratigraphy, Sharp and Epstein consider the over-all agreement impressive. Using the summer peaks of the oxygen-isotope curve they obtain an average accumulation of 14 gm cm^{-2} ; using the winter lows they obtain 16 gm cm^{-2} . For the two-year period, 1957 and 1958, the average accumulation was 15 gm cm^{-2} . This compares extremely well with the stake measurements at S-2; accumulation-movement stakes for the period 20 March 1957 to 10-17 January 1959, 12.9 gm cm^{-2} , Weather Bureau stakes for the period 13 March 1957 to 16 October 1959, 15.9 gm cm^{-2} .

Deep pit at S-2

At the S-2 station, 1166 m elevation, a deep pit was excavated in the firn to allow study of the stratigraphy, density increase with depth, and the annual accumulation of snow. The pit is 2 meters square and 35 meters deep. The pit was dug by three men over a period of three months.

The depth-density data have been tabulated and plotted in the data report by Cameron et al. (1959, pp. 42-47). These data have been analyzed by Bader (1960, 1962) and the analysis is presented in his discussion of the densification of snow on high polar glaciers.

The stratigraphy of the pit was recorded in detail from the surface to a depth of four meters. Here the

combination of grain size, density, ramm hardness, and melt crusts enabled the identification of annual layers. Annual layers are considered to be an amount of accumulation separated by two warm periods. Thus one accumulation year may be from January to January (12 months), or December to January (13 months), or January to December (11 months). However, at the S-2 station the warmest month is probably January and over a number of years the accumulation year probably averages 12 months in length.

From the surface to four meters depth the grain size varied from less than 0.5 to 3.0 mm. Winter snow had a grain size of less than 1.0 mm and summer snow or snow associated with melt features had a grain size of 1.5 to 2.0 mm. There was no indication of any increase in grain size with depth.

The density, hardness, and grain size studies indicated that summer horizons were identical with the position or very close to melt crusts and layers. Thus for the remainder of the pit from 4 meters to 35 meters depth melt crusts or layers were used to indicate the summer horizons.

Melt features recorded in the pit were crusts, layers, pipes or glands and iced firn. Melt crusts were generally 2 to 3 mm thick and could be traced around the walls of the pit. Melt layers were 1 to 2 cm thick, some were continuous but others discontinuous on the wall. At a depth of 2132 cm

in the pit the largest assemblage of melt features was found. Here ice layers reached 4 cm thick and 35 cm long, ice glands or pipes were as much as 4 cm wide and 25 cm high. This melt had infiltrated nearly 175 cm of firn. The many ice pipes and iced firn strata indicate that most of the melt occurred during one very warm summer and infiltrated the layers below.

The summer horizons in the pit were identified by melt features. The amount of the annual accumulation was computed using the average firn density between successive summer horizons and the thickness of this layer. Between the surface and 35 m depth 544 density samples were taken in the wall with a 7.6 cm diameter coring auger. An effort was made to avoid ice layers and pipes.

The annual accumulation, gm cm^{-2} , for the years 1956 to 1783 is plotted in Figure 27. The depth of the summer layer, thickness of the annual layer, the annual accumulation and various means are tabulated in Appendix II. The accumulation for this period of 174 years ranges from 6.0 to 35.0 gm cm^{-2} and averages 13.3 gm cm^{-2} and has a standard deviation of 4.6 gm cm^{-2} .

In Figure 27 accumulation values for each year have been plotted and are connected by a solid line; 5-year running means are plotted and connected by a dashed line. In studying the pattern of the accumulation no increase or decrease with time is evident.

Figure 27.--Annual accumulation in S-2 deep pit from 1783 to 1957.

Conclusions

Snow accumulation in the area between S-1 and S-2 has been well documented by stakes and pits; these data are summarized in Table 16.

The accumulation along the S-2 trail, as recorded by stakes for a two-year period, was 7.9 gm cm^{-2} ; shallow pit measurements gave an average of 9.6 gm cm^{-2} . Stake measurements by the Australians from 1959 to 1962, along the same trail, give an average of 10.3 gm cm^{-2} (Budd, 1963, p. 34).

At S-2 the accumulation at the state net (1.8 years) was 12.9 gm cm^{-2} ; the Weather Bureau stakes (2.5 years) gave 15.9 gm cm^{-2} for the period 1957 to 1962 (Budd, 1963, p. 34). The deep pit average of 13.3 gm cm^{-2} and the $0^{18}/0^{16}$ values for 2 years of 15 gm cm^{-2} establish very well the rate of accumulation at the site.

Between S-1 and S-2 (70 km) there is no pronounced variation in the accumulation due to either elevation or distance from the coast. This suggests a uniformity of precipitation and wind regime.

TABLE 16.--Summary of Annual Accumulation Studies

Site	Elevation (m)	Period (Years)	Annual Accumulation Rate gm cm ⁻²
Sullivan Trail (11 stakes)	345-711	0.8	14.3
S-2 Trail (8 stakes)	467-1091	2.0	7.9
S-2 Accumulation- Movement (12 stakes)	1166	1.8	12.9
S-2 Weather Bureau (3 stakes)	1166	2.5	15.9
Sullivan Trail Shallow Pit	711	5.0	15.2
Pit 10 miles ESE of S-2	1206	3.0	9.7
S-2 Trail Shallow Pits:			
Flag #1	1091	4.0	8.8
Flag #2	1016	6.0	10.1
Flag #3	944	4.0	7.9
Flag #4	861	6.0	10.4
Flag #5	772	1.0	10.0
Flag #6	673	2.0	10.5
O ₁₆ /O ₁₈ at S-2	1166	2.0	15.0
S-2 Deep Pit	1166	174.0	13.3

ICE AND FIRN TEMPERATURES

Introduction

The temperature distribution within a glacier is governed by the shear stress at the base, rate of movement, the accumulation rate, the geothermal gradient of the bed-rock over which the ice flows, and the climate of the surface of the glacier. A study of this temperature distribution from the glacier surface to the glacier bed can provide the mean annual air temperature over the glacier, the geothermal gradient at the bed, and information on the relative rates of movement of different parts of the glacier. In addition, detailed studies of the temperature distribution and fluctuation with time in the upper part of the firn or ice of a glacier can be used to determine the thermal diffusivity and conductivity, of the firn or ice.

Thus a study of the temperatures within a glacier can give a great deal of information on the dynamics of the glacier, the earth temperature below, the climate above, and the thermal properties of the glacier firn or ice.

In an effort to obtain some of this information a series of temperature measurements were taken at a depth of 10 meters along the S-2 trail from an elevation of 36 m to 1206 m, the temperature distribution and fluctuation over a

two-year period was measured in a 16-meter hole in ice at S-1 (252 m elevation) and the temperature distribution in the firn at S-2 (1166 m elevation) was measured from the surface to a depth of 62 meters. Recent measurement of the temperature gradient from the 10 to 28 meter level at a series of sites along the S-2 trail by the Australians has contributed further to the understanding of the temperature conditions of this area.

Ice and Firn Temperatures from the Coast to 96 Km Inland

Introduction

On high polar glaciers the temperature of the firn at a depth of 10 m is approximately equal to the mean annual air temperature at the surface (Wade, 1945, p. 170; Loewe, 1956, p. 663). Thus to determine the temperature regime at the surface of the ice sheet near Wilkes Station, 10-meter temperatures were obtained at four places along the S-2 trail, at S-2, and at a point 16 km east-southeast of S-2, all in the area of little melting. For additional temperature, one measurement was taken in the wet snow zone, one measurement in the superimposed ice zone, and two measurements in the ablation zone; these values, however, are not necessarily equivalent to the mean annual air temperature.

Temperatures were measured with a copper-constantan thermohm and a Leeds and Northrup Wheatstone Bridge Direct Reading Temperature Indicator. The element was lowered to

the bottom of a hole 8 cm in diameter, covered with snow or ice, and allowed to stabilize for a minimum of two hours.

Temperature above the
saturation line

The temperature values obtained from a depth of 10 m and greater along a profile from the coast to 96 km inland, a change in elevation of 1206 m, are given in Table 17 and are plotted in Figure 28. The saturation line or upper limit of complete wetting of the firn as defined by Benson (1962, p. 24) is at about 500 m in elevation. The 10-meter temperatures measured above the saturation line are equivalent to the mean annual air temperature. A plot of the 10-m temperatures versus elevation describes a straight line, determined by the least squares method, representing a mean annual lapse rate of 1.02°C per 100 m. This value is in close agreement to similar determinations made along the periphery of East Antarctica, Table 18. The extension of the mean annual lapse rate line, the dashed line in Figure 28, intersects sea level at a temperature of -7.7°C . Extrapolating the meteorological observations at Wilkes Station which give (for the period March 1957 to February 1958) a mean annual air temperature of -8.1°C at 15 m above sea level, the value at sea level is -8.0°C . At Wilkes Station the observed mean annual air temperature and the value determined graphically from the inland ice temperatures agree to within 0.5°C . This degree of agreement may be

TABLE 17.--Temperature of the Firn and Ice at a Depth of 10 meters

Date	Location	Elevation	Temp. °C	Depth	Material
9 Dec 1957	16 km ESE of S-2	1206	-19.7	10	Firn
28 July 1957	S-2 S-2 Trail:	1166	-19.4	10	Firn
28 Nov 1957	Red Flag #2	1016	-18.0	10	Firn
30 Nov 1957	Red Flag #4	861	-16.3	10	Firn
2 Dec 1957	Red Flag #6	673	-14.7	10	Firn
6 Dec 1957	Red Flag #8	467	-12.2	10	Firn
25 Aug 1958	Black Flag #2 S-1	381 262	-10.5 - 7.7	11 16	Ice Ice
20 Aug 1958	M-3	157	- 7.7	11	Ice
7 Aug 1958	MG	36	- 7.7	11	Ice

large fortuitous but the results indicate that the same lapse rate may be applied over the whole height range down to sea level.

These temperature studies show only the influence of elevation on temperature. The profile studied did not extend far enough inland to make possible the determination of the effects of increased latitude on the temperature. Temperature studies in north Greenland by Langway (1961, p. 1037) show that there is a change of 1°C per 1° of latitude. Schytt (1960, pp. 176-178) has discussed qualitatively the effect on temperature of distance from the coast or

TABLE 18.--Lapse Rates in East Antarctica

Investigator	Station	Longitude	Elevation (M)	Lapse Rate, °C/100 M
Lorius	Dumont d'Urville	140E	0-2400	1.04
Cameron	Wilkes	110E	0-1206	1.02
Bogoslovski	Mirny	93-94	0-2000 2000-3500	1.05 1.27
Mellor	Mawson	63	0-1000 1000-2000 2000	0.9 1.1 1.3

continentality, but he does not deal separately with the effect of latitude. During a traverse inland from Wilkes Station during the summer of 1961-1962 Australian glaciologists collected temperature data which will soon be available for the analysis of the effects of latitude and continentality on temperature.

Temperatures in the saturation zone

In the area below the saturation line (500 m elevation) the 10-meter temperatures do not reflect the mean annual air temperature at the surface. However, the mean annual air temperatures can be ascertained by extending the lapse rate line as determined at higher elevations. For example at 262 m elevation (S-1 meteorological station), the lapse rate line gives a mean annual temperature of -10.3°C , while the mean annual air temperature at S-1 for the period February

1957 to January 1958 as determined from thermograph readings is -10.7°C .

The deviations between the mean annual air temperature and the 10-meter temperature are given in Table 19. The deviation begins near an elevation of 500 m, increases to near 300 m, and then decreases to sea level. The difference between the mean annual temperature and the 10-meter temperature is greatest in the area of the firn line, in this case nearly 3°C .

TABLE 19.--Difference between Mean Annual Air Temperature and the 10-Meter Temperature

Site	Elevation, m	Difference, $^{\circ}\text{C}$
Red Flag #8	467	0.2
Black Flag #2	381	1.0
S-1	262	2.6
M-3	157	1.5
MG	36	0.3

Stratigraphic studies have shown that the area between 500 and 350 m elevation is a soaked firn zone and an area where descending water can transport heat to depth. Superimposed ice is found annually between 350 and 230 m elevation, and the latent heat of fusion contributes to raising ice temperatures at depth. Little heat is available for raising the temperature of the ice in the ablation zone, but some heat may be conducted downward.

Surface melting increases from the saturation line to the firn line because of increasing summer temperatures. In the upper part of this zone firn and ice layer alternate and there is a predominance of firn; in the lower part, near the firn line, there are several firn layers and at the firn line is all ice of density 0.87 gm cm^{-3} . Although there is more melting at lower elevations the increase in the amount of ice (impervious to meltwater) decreases the downward transport of heat. Thus there exists a point between the saturation line and the firn line where there is a maximum downward transport of heat due to percolation; this transport of heat decreases gradually up towards the saturation line and decreases sharply near the firn line.

The effect of this percolation of melt water can be estimated by some simple calculations. At an elevation of 381 m the temperature gradient between the surface and 10 m corresponds to an annual heat transfer to the surface of $t \times \frac{d\theta}{dz} \times k$, per sq. cm (where $t = 3.1 \times 10^7$ seconds and k = the thermal conductivity, here taken as 4×10^{-3} c.g.s Units) $\simeq 180$ cal/sq. cm/yr. Thus, to maintain the temperature gradient at $1^\circ\text{C}/10 \text{ m}$, a quantity of heat equivalent to the latent heat of 2.5 gm/cm^2 of water must be available annually for suitable distribution over the depth range 0-10 m. The details of this process, considering also the annual accumulation and forward movement, are not clear. However, it appears reasonable to suppose that the major

part of the deviation of the observed temperature from the mean annual surface temperature is the region above the saturation line, is due to the percolation of melt water.

At and below S-1, the surface material is ice, of density 0.87 gm cm^{-3} (at S-1) which should be almost impermeable to melt water. Here the percolation of melt water and the transport of latent heat is not possible. In this area the value of $T_{10} - T_0$ decreases with elevation below the balance line. This is in accord with the supposition that in the region above S-1 the annual heat inflow (as latent heat) exceeds the outflow by a small amount. Hence there is an increase of the temperature gradient with time, and hence with distance from the 500 m contour, to a maximum at the level of S-1, where the surface is impermeable, and a reduction at lower elevations.

Other factors should be considered in a full attempt to interpret the observations. These include (1) that the generation of heat by differential flow in the ice, and friction at the base, varies with altitude and should be greatest near the firn line (S-1) and (2) that the albedo of the surface during most of the summer is about 50% at and below S-1, while it is much higher in the snow-covered zone above S-1. The penetration of solar radiation is affected, and the additional absorption in the lower zones may contribute somewhat to the observed temperature gradient.

The 10-meter ice temperatures from 262 m elevation to sea level are all -7.7°C which is the mean annual air temperature at sea level. A decrease in the ice temperature with increased elevation would ordinarily be expected. The reason for this coincidence of temperature values at different elevations is not readily apparent.

Firn Temperatures at S-2

Measurement and results

The temperature of the firn was taken in the wall of the 35 meter deep pit at S-2. Additional temperatures were taken in the hole which was drilled in the pit bottom to 61.84 meters on 10-16 October 1957. As the drilling of the hole at the pit bottom proceeded temperatures were taken at 42 and 52 meters depth and finally at 61.84 meters. A value of -19.60°C was obtained for each of these levels. About the one month later, on 27 November 1957, the temperature at 61.84 m was repeated read as -19.43°C . Since there is little circulation of air in the drill hole, it is doubtful that the temperature at the bottom of the hole could have risen 0.2°C in the one-month period. Thus the temperatures measured at 42, 52, and 61.8 meters during the period 10-16 October 1957 are considered in error. The temperature at 61.8 meters is taken as -19.43°C and the temperatures at 42 and 52 meters are between -19.41° and -19.43°C . Temperature values are given in Table 20 and are plotted in Figure 29.

TABLE 20.--Firn Temperatures at S-2

Date	Depth (cm)	Temp. °C
28 July 1957	25	-17.45
	50	-19.20
	100	-19.70
	200	-20.40
	300	-19.85
	400	-19.65
	500	-19.42
	600	-19.30
	700	-19.35
	800	-19.40
	900	-19.40
	1000	-19.41
	2300	-19.41
10 Oct	4200	-19.60
11 Oct	5200	-19.60
16 Oct	6184	-19.60
27 Nov	6184	-19.43

Conclusions

The annual temperature wave at S-2 probably does not penetrate more deeply than 10 m. The firn temperature between 10 m (-19.41°C) and 62 m (-19.43°C) is essentially the same; thus there is no temperature gradient in this interval. The significance of the absence of a temperature gradient at S-2 is discussed further in the following section.

Temperature Gradients

Australian glaciologists have determined the temperature gradient of the ice sheet for the depth interval 10-28 m at several points along the S-2 trail (Budd, 1963, p. 36).

These values are given in Table 21 and are plotted in Figure 30.

TABLE 21.--Temperature gradients of the 10-28 m Depth interval Along the S-2 Trail

Distance from Coast (km)	Elevation (m)	Temperature Gradient ($^{\circ}\text{C}/100\text{ m}$)
9	262	2.8
11	310	2.5
15	415	2.0
30	615	1.4
63	1015	0.4

The remarkable feature here is that these are all positive temperature gradients, i.e., temperatures increase with depth. In a moving ice sheet the transport of cold snow to lower elevations produces a negative temperature gradient in the upper 50 m on the order of $2^{\circ}\text{C}/100\text{ m}$ above the firn line (Mellor, 1960, p. 777). Along the S-2 trail the positive temperature gradients decrease from $2.8^{\circ}\text{C}/100\text{ m}$ at S-1 to $0.4^{\circ}\text{C}/100\text{ m}$ at 63 km inland, an indication of little movement at S-1 increasing gradually toward S-2. Budd (1963, p. 36) has estimated that at S-2 there would be no temperature gradient; this is in accord with the measurements reported above.

Budd states that south of S-2 the temperature gradients are negative at 2° to $3^{\circ}\text{C}/100\text{ m}$. Thus inland of S-2 ice motion increases. Thus it seems that the Windmill

Figure 30.--Temperature gradients of the 10-28 m depth interval along the S-2 Trail. Measurements made by Australian glaciologists.

Islands restrict the forward motion of the ice sheet at least as far inland as S-2.

Moving on the margin of an ice sheet generally has a negative temperature gradient but when the ice becomes stagnant and thin then the temperature gradient is positive and approaches the geothermal gradient below. In Figure 30 the plots of the temperature gradients along the S-2 trail have been joined by a curved line. From 600 m to 1166 m (S-2) the line is essentially straight but below this the gradients increase more rapidly. This is possibly due to the increased influence of the geothermal heat in this thinner ice. Continuing this line to sea level a temperature gradient of $4.9^{\circ}\text{C}/100\text{ m}$ is obtained which approximates the geothermal gradient. At Mirny, Bogoslovski (1958, p. 287) studied the temperature distribution in 64 m of ice (frozen to its bed) and several meters of glacial bed, and obtained a geothermal gradient of $5.1^{\circ}\text{C}/100\text{ m}$. Both Wilkes and Mirny areas consist of igneous and metamorphic rocks and there is no reason to suppose that the geothermal heat flow varies appreciably from the one site to the other. A 'normal' heat flow of 1×10^{-6} cal/sq. cm/sec produces a temperature gradient in stagnant ice of $2.6^{\circ}\text{C}/100\text{ m}$.

It seems significant that the temperature gradients in Figure 30 begin to deviate from a straight line at about 500 m elevation and the 10-meter temperatures in Figure 28 start to deviate at about the same elevation. Thus it seems

that the temperatures within the stagnant and near stagnant ice below 500 m elevation are strongly influenced both by the geothermal heat from below and the downwind transport of heat by meltwater from above. It is also likely that the glacier is frozen to its bed as far inland as the 500 m contour (20 km inland).

Ice Temperatures at S-1

Introduction

The temperature of the upper 16 m of the ice was recorded during a period of 26 months at S-1 8 km east-southeast of Wilkes Station at an elevation of 262 m.

Stability of the surface.--S-1 is near the balance line of accumulation and ablation. However, the elevation of the snow line and the lower limit of superimposed ice can vary by more than 50 m from one year to another; the snow line may be as high as 375 m elevation and the superimposed ice limit as low as 225 m. Thus S-1, at 262 m, may be in the accumulation area (superimposed ice) one year and the ablation area the next.

In the summer of 1956-1957 ablation was great and the balance line was considerably above 262 m. During the winter of 1957 very little snow accumulated and extensive areas remained as bare ice throughout the winter. The immediate area where the ice temperature measurements were taken was covered by not more than 20 cm of snow during the year.

Slush which formed at the surface during the summer of 1957-1958, froze during the fall, raising the surface, relative to the buried thermohms, by 0-8 cm (Hollin, et al., 1961, p. 199). Snow cover during the winter of 1958 was again variable, with patches of ice remaining uncovered throughout the year. However, the summer of 1958-1959 was cooler and a snow accumulation equivalent to 15 gm cm^{-2} was recorded by Cronk at S-1 for the period February 1958 to February 1959.

During the period of temperature observations the accumulation and ablation were nearly balanced. The snow cover at the temperature--measuring site was less than 30 cm at all times; $0-7 \text{ gm cm}^{-2}$ of superimposed ice accumulated during 1957, and 15 gm cm^{-2} of snow accumulated from February 1958 to February 1959. No detailed measurement was made of the incremental accumulations of snow and ice at the temperature site; however, the total accumulation near S-1 was so small during the 769-day period of temperature measurements that, in the following discussion, the surface is considered to be stable and the thermohm depths absolute.

Density of the ice.--Density measurements of the ice near S-1 were made by Hollin (1961, p. 220). He found that white, very bubbly ice from the surface 12 cm (probably frozen slush) had a density of $0.76 \pm 0.02 \text{ gm cm}^{-3}$. Below this to 11 m depth, the ice was blue and moderately bubbly with a density of $0.87 \pm 0.02 \text{ gm cm}^{-3}$. Some thin strata

were nearly bubble-free and had a density of 0.90 ± 0.02 gm cm⁻³. From 11 to 16 m depth there was no apparent change in the character of the ice so it can be assumed that density variations with depth are small.

Instrumentation and measurement.--The temperature-sensing elements were placed in the ice on 22 and 23 February 1957. A hand-operated core drill was used to drill holes 11 cm in diameter 0.5, 2, 4, and 16 m deep. The four holes were drilled in a straight line at 25 cm intervals. Elements were placed at the bottom of the 0.5, 2, and 4 cm holes and at the 7, 11, and 16 m levels in the 16 meter hole. The holes were then completely filled with ice chips. An additional element was placed just below the ice surface to enable the surface temperature to be recorded, but by the end of the 1957-1958 summer, the element had melted 10 to 20 cm into the ice.

The sensing elements consisted of copper-constantan thermohms with leads to a junction box and a selector switch. Temperatures were read with a Leeds and Northrup Wheatstone Bridge Direct Reading Temperature Indicator. Readings were made to the nearest 0.01°C but are probably accurate only to the nearest 0.05°C and may include errors discussed below.

The ice temperatures were measured on 101 times between 25 February 1957 and 14 April 1959, a period of

769 days. The surface thermohm, however, was operative for only 434 days from 18 March 1957 to 26 May 1958 at which time it was damaged.

Correction of measured temperatures.--Temperatures read on the Indicator are subject to some errors, such as those due to variations of the resistance of the potentiometer coils. To minimize these errors two procedures were adopted: (A) one position of the selector switch was connected to a check coil designed to read -2.20°C . Deviations from this value, at the time of reading temperatures at depth, were applied as corrections to all the temperature readings. (B) on the assumption that the annual variation of temperature at the 16 m level is sinusoidal, with a period of one year² (following Schytt, 1960), temperatures at this depth, corrected as in procedure (A), were fitted to a sinusoidal curve, the deviations were assumed to be extra corrections and these corrections were then applied to temperatures at all depths. Corrections from procedure (A) vary from 0 to 1.40°C and, from procedure (B) from 0 to 1.28°C .

Observed values of temperature, corrected in this way, are given in Table 22. These tabulated values have a probable error of 0.2°C .

²The amplitude of a sinusoidal temperature wave decreases exponentially with depth, the exponent being inversely proportional to the period. At a depth of 16 m all components of the surface temperature variation, except the largest (one year) are damped out.

TABLE 22.--Corrected Temperatures ($^{\circ}\text{C}$) at Various Depths in the Ice at S-1

Date	Depth						
	Surface	0.5 m	2 m	4 m	7 m	11 m	16 m
1957							
February	25		1.89	1.21	4.31	7.12	8.01
	27		2.11	1.41	4.27	7.06	8.01
March	4		3.27	2.22	4.42	7.02	8.02
	18	4.54	4.55	3.31	4.36	6.62	7.85
	26	6.69	5.34	3.94	4.44	6.44	7.79
April	1	6.18	6.03	4.48	4.63	6.43	7.78
	8	9.28	6.43	4.73	4.73	6.28	7.68
	17	6.40	8.00	5.60	4.98	6.19	7.50
	19	5.85	7.25	6.60	5.05	6.20	7.60
	20	5.65	6.93	5.95	5.10	6.25	7.55
	21	5.38	6.59	5.96	5.13	6.19	7.55
	22	7.45	6.55	6.04	5.23	6.23	7.55
	23	7.53	6.53	6.00	5.22	6.22	7.53
	25	6.35	6.63	5.97	5.30	6.16	7.54
	26	8.66	6.54	5.98	5.33	6.20	7.53
	27	9.93	7.00	5.97	5.42	6.24	7.52
	28	11.31	7.51	5.98	5.44	6.27	7.52
May	30	9.47	8.00	6.01	5.51	6.22	7.48
	1	10.24	8.02	6.09	5.52	6.28	7.50
	2	10.24	8.22	6.12	5.51	6.23	7.50
	3	11.70	8.46	6.19	5.51	6.23	7.50
	4	14.17	8.93	6.20	5.59	6.25	7.43
	5	15.06	9.72	6.31	5.53	6.19	7.44
	6	13.01	10.35	6.47	5.67	6.28	7.50
	13	11.11	9.38	7.25	5.83	6.29	7.31
	20	12.39	10.69	7.64	6.04	6.24	7.29
June	3	12.49	11.03	8.67	6.64	6.36	7.24
	10	21.07	14.45	8.97	6.86	6.50	7.17
	19	18.78	17.85	11.34	7.29	6.54	7.11
	27	15.81	14.46	11.97	7.80	6.58	7.11
July	1	18.50	15.87	11.87	9.14	6.70	7.17
	10	16.28	15.44	12.36	8.75	6.89	7.13
	17	14.79	14.83	12.44	9.09	7.00	7.13
	21	16.73	14.98	12.35	9.56	7.08	7.08
	30	16.92	15.40	12.62	9.51	7.31	7.08

TABLE 22.--Continued

Date		Depth						
		Surface	0.5 m	2 m	4 m	7 m	11 m	16 m
August	6	15.76	15.12	12.76	9.83	7.58	7.13	7.52
	12	16.60	15.48	12.88	9.91	7.63	7.15	7.51
	29	12.27	12.66	12.72	10.44	8.17	7.39	7.50
September	5	13.79	12.90	12.25	10.43	8.16	7.26	7.50
	12	12.30	12.72	12.20	10.40	8.18	7.31	7.51
	21	15.47	13.69	12.11	10.47	8.55	7.46	7.52
	29	12.18	12.79	12.21	10.63	8.76	7.57	7.54
October	5	13.40	12.15	12.06	10.58	8.80	7.64	7.55
	12	9.98	10.75	11.68	10.51	8.78	7.65	7.56
	20	12.63	12.13	11.32	10.49	8.87	7.72	7.58
November	4	9.05	10.80	11.35	10.40	9.05	7.80	7.60
	11	8.42	9.57	10.82	10.32	9.02	7.88	7.62
	18	8.23	9.18	10.48	10.28	9.08	7.88	7.68
	25	7.84	8.51	10.00	10.09	9.09	7.81	7.65
December	2	7.81	7.89	9.56	10.55	9.03	7.95	7.67
	8	6.13	7.38	9.28	9.88	9.13	8.03	7.68
	10	5.59	7.18	9.27	9.84	9.13	7.96	7.68
	16	2.71	5.51	8.65	9.56	9.04	8.01	7.70
	23	0.17	2.95	7.61	9.36	9.00	8.00	7.72
	31	0.25	2.25	6.53	8.92	8.95	8.14	7.69
1958								
January	6	0.55	2.20	6.00	8.65	8.95	8.20	7.75
	14	0.37	0.62	5.07	8.17	8.82	8.22	7.77
	23	0.00	0.08	4.28	7.68	8.68	8.18	7.78
	27	0.00	0.00	3.32	6.96	8.45	8.10	7.79
February	3	0.00	0.00	2.40	6.30	8.30	8.20	7.80
	10	0.00	0.00	2.23	6.16	8.16	8.16	7.81
	17	0.00	0.09	2.19	5.72	7.99	7.94	7.61
	24	1.14	0.54	2.33	5.60	7.89	8.12	7.82
March	3	2.51	1.40	2.83	5.40	7.79	8.17	7.82
	10	4.15	2.50	3.08	5.15	7.54	8.05	7.81
	17	4.80	4.40	4.00	5.30	7.35	8.00	7.80
	24	3.21	4.88	4.57	5.42	7.16	8.00	7.79
	31	7.52	6.08	4.67	5.39	7.09	7.95	7.78

TABLE 22.--Continued

		Depth							
Date		Surface	0.5 m	2 m	4 m	7 m	11 m	16 m	
April	7	7.72	6.82	5.62	5.62	6.97	7.87	7.77	
	14	6.41	6.26	5.86	5.66	6.86	7.86	7.76	
	21	11.35	9.10	6.20	5.90	6.80	7.75	7.75	
	28	8.33	8.38	7.48	6.08	6.78	7.68	7.68	
May	5	11.43	10.26	7.66	6.44	6.85	7.66	7.72	
	12	8.73	9.72	6.44	6.66	6.69	7.41	7.70	
	19	6.58	7.66	8.27	7.06	6.88	7.65	7.69	
	26	9.90	9.83	7.86	7.11	6.92	7.50	7.69	
June	2		11.78	8.76	7.35	7.05	7.54	7.66	
	9		13.60	10.04	7.55	7.11	7.43	7.64	
	16		16.10		7.91	7.08	7.42	7.62	
	24		16.83	12.18	8.24	7.18	7.41	7.60	
July	1		18.79	13.94	8.79	7.26	7.39	7.59	
	9		14.96	13.99	9.51	7.46	7.38	7.57	
	14		13.18	13.25	9.86	7.60	7.38	7.56	
	21		12.45	12.45	10.05	7.70	7.40	7.55	
	28		13.72	12.29	10.17	7.93	7.42	7.53	
	4		14.70	12.52	10.12	7.92	7.32	7.52	
	11		15.57	12.87	10.22	8.10	7.37	7.52	
	19		15.50	13.57	10.40	8.25	7.43	7.50	
	25		14.92	13.47	10.69	8.35	7.50	7.50	
	September	2		14.35	13.50	10.90	8.55	7.55	7.50
		8		14.71	13.21	11.01	8.71	7.61	7.51
		15		16.92	13.52	11.12	8.82	7.72	7.52
November	17		11.38	12.45	12.07	10.11	8.36	7.63	
	24		10.33	11.60	11.67	9.90	8.14	7.65	
December	8		8.88	10.46	11.23	9.95	8.23	7.68	
	29		6.37	8.72	10.49	9.94	8.44	7.73	
1959									
January	6		6.10	8.13	10.02	9.85	8.50	7.75	
February	24		5.42	6.42	8.42	9.22	8.72	7.82	
March	18		7.30	7.10	7.70	8.60	8.50	7.80	
	27		9.09	7.69	7.79	8.59	8.39	7.79	
April	14		7.66	8.16	8.06	8.06	8.16	7.76	

Results

General.--The temperature values given in Table 22 are plotted in Figure 31 and the temperature data for the two years, 18 March 1957 to 17 March 1958 and 17 March 1958 to 18 March 1959, are summarized in Table 23. Maximum and minimum range and mean values of temperature are taken from Table 22 while amplitude values have been obtained from five-observation running means. Weekly observations were made until 15 September 1958 when observations were discontinued until 17 November 1958. From this date to 14 April 1959 only one or two observations were made each month. Thus from September 1958 to April 1959 the five-observation running means are not readily comparable to the preceding values.

Temperature curves.--The temperature curves in Figure 31 show the annual temperature wave recorded at each thermohm. At the surface these are small amplitude short-period temperature fluctuations departing from the annual sinusoidal wave. Because their amplitude decreases rapidly with depth they are very small at 2 m and negligible at 4 m depth. The maximum temperatures at the surface (0°C) occurred between mid-December and mid-February and the surface minimum temperatures was registered in June and July. These maxima and minima are displaced at depth due to the finite velocity of penetration of the temperature wave. The 0.5 m curve shows that the summer of 1957-1958 was warm, this level being at 0°C between mid-January and mid-February, while the summer

Figure 31.--Five-observation running-mean temperatures for each thermohm for the period 25 February 1957 to 14 April 1959.

TABLE 23.--Temperature Data, -°C

Thermohm Depth (m)	1957-1958					1958-1959					2 Year Mean
	Maxi- mum	Mini- mum	Range	Ampli- tude	Mean	Maxi- mum	Mini- mum	Range	Ampli- tude	Mean	
0	0.00	21.07	21.07	9.05	8.95	---	---	---	9.15 ¹	12.54 ¹	10.75 ¹
0.5	0.00	17.85	17.85	7.85	8.28	4.40	18.79	14.39	8.03	11.10	9.69
2	2.19	12.88	10.69	5.14	7.79	4.00	13.57	9.57	5.53	9.79	8.79
4	4.36	10.63	6.27	3.09	7.46	5.30	12.07	6.77	2.92	8.59	8.03
7	6.16	9.13	2.97	1.45	7.45	6.69	10.11	3.42	1.58	7.91	7.68
11	7.08	8.22	1.14	0.51	7.63	7.32	8.72	1.40	0.57	7.75	7.69
16	7.50	7.81	0.31	0.51	7.68	7.50	7.82	0.32	0.16	7.65	7.67

¹These values have been extrapolated as the surface thermohm was broken after 26 May 1958.

of 1958-1959 was much cooler and the ice at this depth probably did not become warmer than -4°C .

The temperature curve during the winter of 1957 was relatively flat and had no pronounced minimum whereas the 1958 minimum shows mid-winter reversals. This is best shown on the temperature curve for 0.5 m. This flat minimum, with reversals of the expected seasonal trends, is called a kernlose or coreless winter.

Mean temperatures.--The mean temperatures at each depth for the two separate years and for the entire two-year period are plotted in Figure 32. The mean temperature at the surface, computed for March-to-March, is comparable to the November-to-November mean temperature at 16 m depth, due to the finite time of penetration of the temperature wave. Table 24 presents a March-to-March comparison but it is understood that the temperatures recorded by the thermohms at depths greater than 4 m are reflecting the surface temperature fluctuation of earlier time intervals. The upper 2 m of the ice, which responds rapidly to temperature fluctuations of the air above, clearly shows that the 1958-1959 year was considerably cooler than the 1957-1958 year. Table 24 shows that the mean annual temperature at the surface in 1958-1959 was 3.6°C lower than in 1957-1958.

Figure 32.--Mean temperature for each thermohm for the periods 1957-1958, 1958-1959, and 1957-1959.

TABLE 24.--Differences of Mean Temperature in the Ice at S-1, at Selected Depths, between 1957-1958 and 1958-1959

Depth (m)	Number of degrees C
0	3.59 ^a
0.5	2.82
2	2.00
4	1.13
7	0.46
11	0.12
16	0.02 ^b

^aExtrapolated.

^b1957-1958 cooler.

Velocity of a travelling temperature wave.--The penetration of the 1957-1958 summer surface maximum temperature wave has been used to compute the velocity of the travelling wave. Table 25 gives the dates of arrival of the temperature maxima at the various depths. The surface and 0.5 m maxima are thought to have occurred when 0°C was first reached. The dates of arrival of the temperature wave at depth were obtained from the five observation running means. The date of the maximum temperature at 11 and 16 m depth is difficult to select precisely, due to the small amplitude, so only the interval during which it arrived is given. Figure 33 is a plot of the arrival times of the temperature wave at various depths.

TABLE 25.--Date of Maximum Temperature at Each Thermohm

Depth (m)	Date (1958)	Number of Days
0	19 January	0
0.5	25 January	6
2	17 February	29
4	17 March	57
7	3 May	104
11	24 June-14 July	156-176
16	14 August-12 September	207-236

The velocity of the temperature wave is given as:

$$V = \frac{x}{t} \quad (1)$$

v represents velocity in cm sec^{-1} ; x , depth in cm; and t , time in seconds. The line which best fits the arrival times in Figure 33 intersects the 16 m level at 236 days.

Substituting in (1):

$$v = \frac{1,600}{20,390,400}$$

$$v = .785 \times 10^{-4} \text{ cm sec}^{-1}$$

$$= 6.78 \text{ cm day}^{-1}$$

$$= 24.74 \text{ m yr}^{-1}$$

This is the velocity at which the wave is travelling and is not the rate at which heat energy is transferred across a surface (heat flux).

Figure 33.--The velocity of penetration of the 1957-1958 summer "heat wave."

The velocity has not been determined from the "cold" waves, for the kernlose winters obscure the temperature minima and decrease reliability in selecting the arrival date.

Decrease of wave amplitude with depth.--The decrease with depth of the amplitude of the annual temperature wave has been computed and appears in Table 23. The 1957-1958 year amplitudes decrease from 9.06°C at the surface to 0.15°C at 16 m, and during 1958-1959, the amplitudes decrease from 9.15°C at the surface to 0.16°C at 16 m. The decrease, with depth, of the amplitude of the annual temperature wave is plotted semilogarithmically in Figure 34; the straight lines are defined by the following equations where x is depth in meters:

for 1957-58

$$\text{Amplitude, } ^{\circ}\text{C} = 9.05 \exp (-0.2549x) \quad (2)$$

for 1958-59

$$\text{Amplitude, } ^{\circ}\text{C} = 9.15 \exp (-0.2506x) \quad (3)$$

Interpretation

General.--For periodic flow of heat in one direction through a semi-infinite, homogeneous solid the Fourier equation is

$$\frac{d\theta}{dt} = \alpha \frac{d^2\theta}{dx^2} \quad (4)$$

where α is the thermal diffusivity; t , time; x , distance; and θ , the temperature.

Figure 34.--Variation of amplitude of the annual temperature wave with depth for 1957-1958 and 1958-1959.

If the temperature at the surface is given by $\theta = \theta_0 \cos \omega t$, then the temperature at a depth x is given by

$$\theta = \theta_0 e^{-x \sqrt{\omega/2\alpha}} \cos(\omega t - x \sqrt{\omega/2\alpha}) \quad (5)$$

From this it may be shown that the velocity, V , of the penetration of the temperature wave is

$$V = \sqrt{2\omega\alpha} \quad (6)$$

and the amplitude of the temperature fluctuation at a distance x from the surface is

$$\theta_x = \theta_0 e^{-x \sqrt{\omega/2\alpha}} \quad (7)$$

Before applying these equations to the situation at S-1, the assumptions involved must be justified. The first assumption is that the surface temperature wave is a plane sinusoidal wave of period one year. At S-1 the surface slope is less than 2° ; therefore, with a mean vertical air temperature gradient of 1°C per 100 m, the gradient at the ice surface is about 1°C per 3 km. Although the temperature at the surface is not a simple sinusoidal wave, containing, as it does, smaller amplitude components of shorter periods, the pressure of the short-period components in no way affects the penetration of the large amplitude annual wave, nor its attenuation with depth.

The second assumption is that the material is homogeneous. The density of the ice at S-1 to a depth of 11 m is constant at $0.87 \pm 0.02 \text{ gm cm}^{-3}$, and is unlikely to change significantly between 11 and 16 m. Hence the thermal diffusivity, α ,

$$[\alpha = \text{thermal conductivity}/(\text{specific heat}) (\text{density})]$$

will change with depth only because of changes in the specific heat and thermal conductivity as the temperature varies. The mean temperature varies slowly with depth at S-1; but over the range of temperatures encountered (0 to -20°C) the specific heat of pure ice decreases 0.35% per centigrade degree decrease of temperature, whereas the thermal conductivity of pure ice increases 0.41% per centigrade degree decrease of temperature. Since the mean temperature at S-1 varies only 3°C between the surface and 16 m, the thermal diffusivity should remain constant within 2%, providing that glacier ice behaves in a way similar to pure ice.

The third assumption is that the depth of the thermohms remains constant. The mean accumulation rate at S-1 of less than 7 cm of ice per year over the two-year period is negligible, compared with the velocity of penetration of the temperature wave, $24.72 \text{ m year}^{-1}$.

Independent of the effects of the annual temperature wave, a temperature gradient exists in the ice. This gradient is caused by the geothermal heat flow, the release of frictional heat by differential movement within the ice and sliding of the ice over the bed, and the transport of "cold ice" from higher altitudes on the ice sheet. As long as it remains constant, this temperature gradient does not affect the velocity of penetration of the surface wave, or the decrease of its amplitude with depth.

Thermal diffusivity and thermal conductivity.--Values for thermal diffusivity and thermal conductivity have been determined based on the following assumptions: (1) the annual temperature wave penetrates perpendicular to the surface, (2) the specific heat of the ice is $0.49 \text{ cal/gm}^\circ\text{C}^{-1}$, and the ice has a density of 0.87 gm cm^{-3} . These values have been derived from Equations (6) and (7), and are given in Table 26.

Discussion.--Many determinations of the thermal properties of firn have been made under field conditions, but the only published values for glacier ice are those of Koch and Wegener (1930, pp. 220-221):

$$\alpha = -12.53 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-1}$$

$$k = 5.48 \times 10^{-3} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ }^\circ\text{C}^{-1}$$

These values were obtained from studies of Storstrømmen in north Greenland; the ice had a density of 0.911 gm cm^{-3} and

TABLE 26.--Values of Thermal Diffusivity and Thermal Conductivity for the Glacial Ice at S-1

Method of Computation	Diffusivity, α , $\times 10^{-3}$ cgs	Conductivity, k , $\times 10^{-3}$ cgs
Velocity of travelling wave (Eq. 6)	15.5 ± 0.6	6.61 ± 0.24
Amplitude decrease with depth, 1957-1958 (Eq. 7)	15.3 ± 0.25	6.25 ± 0.10
Amplitude decrease with depth, 1958-1959 (Eq. 7)	15.6 ± 0.1	6.62 ± 0.04
Mean	15.5 ± 0.4	6.69 ± 0.19

Specific heat, $0.49 \text{ cal gm}^{-1} \text{ }^{\circ}\text{C}^{-1}$.

Density, 0.87 gm cm^{-3} .

Mean temperature at surface, -10.7°C (Range, -21.1 to 0°C).

Mean temperature at 16 m, -7.7°C .

a specific heat of $0.48 \text{ cal gm}^{-1} \text{ }^{\circ}\text{C}^{-1}$, and the temperature at the surface was between -25.2 and -28.6°C and the temperature at 24 m was -13.9°C .

The results of many laboratory experiments with pure ice are summarized in Table 27. The mean values at 0°C are:

$$\alpha = 11.6 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-1}$$

$$k = 5.3 \times 10^{-3} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ }^{\circ}\text{C}^{-1}$$

Koch and Wegener's values for α and k exceed those for pure ice by 8% and 4% respectively, which is probably the order of accuracy of their experiments, but the values

TABLE 27.--Thermal Properties of Pure Ice as Determined by Laboratory Experiments

Investigator or Source	Density gm cm ⁻³	Temper- ature °C	Diffusivity, α , x 10 ⁻³ cgs	Conductivity, k, x 10 ⁻³ cgs
#NEUMANN (1863)	0.92	0	11.4	<u>5.3</u>
#TAIT (1886)	0.92	0	<u>10.7</u>	5.0
#STRANEO (1897)	0.92	0	<u>11.2</u> <u>10.7</u>	5.2 5.0
#SCHOFIELD AND HALL (1927)	0.92	0	<u>11.2</u>	5.2
#JAKOB AND ERK (1929)	0.92	0	<u>11.4</u>	5.3
# VAN DUSEN (1929)	0.92	0	<u>10.7</u>	5.0
#ARZYBYSCHEW AND PARFIANO- VICH (1929)	0.92	-3*	<u>12.0</u>	5.5
INGERSOLL, ZOBEL AND INGERSOLL (1954)	0.92	0	11.8	<u>5.5</u>
LANDAUER AND PLUMB (1956)	0.92	-5	<u>10.6</u>	4.8
POWELL (1958)	0.92	-10	<u>11.4</u>	5.1
Accepted Values	0.92	0	11.6	5.3

#See Dorsey, 1940, pp. 481-482.

*Approximate.

Underlined values calculated by present author.

of α and k for the ice at S-1 exceed those for pure ice by 32% and 22% respectively. These divergencies exceed the known experimental errors in the S-1 data by a factor of three. Various mechanisms have been suggested to account for these high values of thermal diffusivity and thermal conductivity compared with those of pure ice at 0°C. Some of these are as follows:

1. The direct effect of the decreased temperature.

The experiments of Jakob and Erk (1929), with pure ice, as reported in Dorsey (1940, p. 482) show an increase in thermal conductivity from 5.30×10^{-3} cal $\cdot$ cm $^{-1}$ sec $^{-1}$ °C $^{-1}$ at 0°C to 5.48×10^{-3} at -10°C. If the same rate of increase with decrease in temperature occurs for the glacier ice at S-1, the divergence in thermal conductivity is reduced to 19%. The specific heat of pure ice decreases from 0.502 cal $\cdot$ gm $^{-1}$ °C $^{-1}$ at -2.2°C to 0.486 at -11°C (Handbook of Chemistry and Physics, 1959). If the same rate applies to glacier ice, the divergence in the thermal diffusivities is reduced to 26%.

2. The effect of impurities. Glacial ice is not pure.

It may contain salts, particularly NaCl, and other foreign matter which might increase the thermal conductivity. The ice from S-1 has not been analyzed and its chemical composition is not known. However, measurements of the electrical conductivity of melted samples of the ice indicate that the salt content is very low (Hollin, et al., 1961, p. 195).

The ice at S-1 is also free of any dust or dirt so impurities are probably not influencing the thermal conductivity.

3. The effect of oriented crystals. Landauer and Plumb (1956, p. 4) have shown that "if a difference in conductivity exists (parallel to and perpendicular to the optic axes)³ of ice crystals it is less than 8%." At S-1 ice has been shown to be randomly oriented (Hollin, et al., 1961, p.192); therefore, the high thermal conductivity cannot be attributed to this cause.

4. The effect of thermal radiation within the ice. Most of the laboratory experiments have been made under steady-state conditions, with a constant temperature gradient maintained across the specimen; Koch and Wegener's determination and the present one are non-steady-state determinations. A small difference between the thermal conductivity obtained under steady-state and non-steady-state conditions has been noted with other materials. This difference has been attributed to the contribution of thermal radiation to the conduction of heat (Van der Held, 1953, 1954). Order-of-magnitude calculations for ice suggest that, at prevailing temperatures, thermal radiation does not account for more than 2% of the total heat transferred, and that the difference in the radiation effect in the two types of experiments should be small.

5. The effect of solar radiation. The present investigation is complicated by the absorption of solar radiation

throughout the depth of ice in which the temperature is measured. The effect is not likely to be large enough to account for the observed differences in thermal conductivity, but the effects of solar radiation and thermal radiation should be more fully considered before other explanations are attempted.

The thermal diffusivity and thermal conductivity of the bubbly glacial ice at S-1 are much greater than those of pure ice under laboratory conditions, but this difference is not yet explained.

Conclusions

The study of the firn and ice temperatures from sea level to 1206 m (96 km inland) give a mean lapse rate of $1.02^{\circ}\text{C}/100\text{ m}$ which is similar to other values determined along the coast of East Antarctica. A marked change in temperature regime occurs at about 500 m elevation which is probably due to the downward percolation of meltwater, the sudden change from a firn surface (high albedo) to a bare ice surface (low albedo) and subsequent increased absorption of incoming solar radiation, the difference in the thermal properties of heterogeneous material (firn and ice) and homogeneous material (ice), and the relatively thin ice being influenced by the geothermal gradient. The geothermal gradient near the ice edge is probably between 4° and $5^{\circ}\text{C}/100\text{ m}$ and is essentially the same as determined

at Mirny. The temperature gradient between 10 and 28 m depth from S-2 to S-1 are positive and indicate that ice motion decreases steadily from S-2 to the coast where the ice is stagnant and frozen to the bed. This demonstrates the influence of the Windmill Islands on the pattern of ice sheet movement.

The study of the ice temperatures to 16 m depth at S-1 show that the value of thermal diffusivity and conductivity for ice of density 0.87 gm cm^{-3} are about 30% higher than the corresponding values for pure ice of density 0.91 gm cm^{-3} . However, no adequate explanation can be presented.

ICE MOVEMENT

Introduction

Little information is available at present on the amount of ice being discharged to the sea by the Antarctic ice sheet. To obtain a realistic appraisal of the mass balance of the ice sheet this discharge along the coast and the amount of snow accumulation over the entire ice sheet must be known. Today the distribution of snow accumulation over the continent is relatively well known; maps have been prepared showing the distribution of accumulation (Cameron and Goldthwait, 1961, Kotlyakov, 1961, and Rubin, 1962) and values have been computed for the total accumulation. These maps and values are being refined regularly with newly acquired data, thus the positive side of the mass balance is fairly well established. However, the total loss of ice from the continent by calving, surface and bottom melting, and sublimation are little known. The calving or ice discharge by icebergs is by far the major form of ablation, possibly amounting to 95%. Thus for a complete understanding of the mass balance of the Antarctic ice sheet the rate of discharge along the varied coastline must be determined.

The following discussion of ice movement along the Budd Coast contributes to the understanding of the rates of

ice discharge along a varied ice margin. Here the margin of the continental ice includes ice terminating on land, part of the ice sheet moving with normal velocity directly into the sea, and an ice stream, the Vanderford Glacier, into which ice is channelled and in which ice velocities greatly exceed those in neighboring parts of the ice sheet. This information on discharge is necessary for determining the regime of the Antarctic ice sheet along the Budd Coast. The same techniques can be used elsewhere so that the over-all ice discharge from the periphery of the glacier can be determined.

Along the Budd Coast ice movement measurements were made of the Vanderford ice stream, the ice abutting the Windmill Islands, and the ice front at Cape Folger.

Vanderford Glacier

Introduction

The Vanderford Glacier is a 12 kilometer broad ice stream which flows north-northwest from within the ice sheet and terminates in Vincennes Bay as a floating ice tongue, Figure 35. The length of the glacier is not precisely known but a traverse in 1958, led by John Hollin, was able to cross the inland extension of the glacier, with little difficulty, at a point 100 kilometers from the coast. Some crevasses were evident but a distinct ice stream could not be distinguished at this distance inland.

Figure 35.--Aerial view, southeast, of the Vanderford Glacier. Ice front in foreground. Note waves on glacier surface.

The subglacial topography is a very large valley (Jewell, 1962) which continues to the coast and to the sea as a fjord. Where the ice is thick, 100 km inland, this valley does not greatly affect the surface form of the ice sheet but towards the coast where the ice is thinner, ice is channelled into the valley, in which its forward velocity is great, and here the ice surface is affected by the subglacial valley.

The surface of the ice stream consists of a series of broad crests and depressions, both highly crevassed. The northeast border of the ice stream is delimited by a distinct ice ridge produced by the shearing of the fast moving ice stream against the slow moving ice sheet. The southwest border is not clearly defined for the ice mass which it abuts is also moving seaward at a modest rate so that there is less shearing. The glacier is afloat for at least 35 kilometers inland.

A baseline for triangulating the stakes on the glacier was laid out on Haupt Nunatak, 15 km inland from the glacier terminus. This nunatak is a group of rock outcrops, 85 m elevation, which project 20 m above the surrounding ice.

From the baseline a good view is obtained of the east side of the ice stream but the center of the glacier is at the same elevation as the baseline so that the west side of the glacier is not visible. Hence the survey from the baseline is confined to the east side. The chaotic surface of

the glacier prevented the extension of the survey to the west side, from points in the middle of the glacier.

The movement of the glacier was measured by two successive U.S.-IGY glaciological parties over the period 3 March 1957 to 30 November 1958.

Method of measurement

A line of stakes was set in the ice from Haupt Nunatak out onto the ice stream for a total distance of nearly five kilometers. The angles to stakes on this profile were taken from the ends of the baseline. The markers near the baseline were bamboo poles with orange flags but these were difficult to see over the great distances so 2" x 4" wooden stakes were substituted at the farther points. The stakes had a wide board across the top and the upper portions were painted black, making them readily visible.

The baseline is 435.17 meters along and is at an angle of 20° with the direction of ice flow at the middle of the glacier. The baseline could not be taped; its length was computed from the angles taken from the ends of a taped subbaseline.

The survey in 1957 was made with a Dietzgen transit and in 1958 with a Kern DKM2 theodolite and a Wild 72 theodolite.

Movement

The coordinates for the positions of the movement stakes at the time of each survey is given in meters in Appendix III, and these positions are plotted in Figure 36. The displacement of the stakes in meters, the direction of this displacement in degrees relative to the baseline, and the rate of displacement in meters per day are given in Table 28. I am grateful to Olav Løken and Caspar Cronk for these computations.

Stakes 1, 2, and 4A moved very little. The direction of movement recorded changes with time and the area in which these stakes were placed is obviously not part of the ice stream. The surface velocity of the ice stream increases from 0.06 m/day at Stake 4 near its edge to 2.12 m/day near its mid-point at Stake 11. A plot of the velocity across the measured profile is shown in Figure 37.

The direction of movement of the stakes varies across the glacier. Stake 11 is considered to be moving directly down glacier and to be representative of the middle of the glacier. This direction is arbitrarily taken as 0 degrees (it is actually north-northwest) and the difference of the movement direction of the other stakes from this arbitrary zero is as follows:

Figure 36.--Vanderford Glacier movement stake positions, March 1957 to 30 November 1958.

TABLE 28.--Vanderford Glacier Stake Displacement

Period	3 March 1957 to 1 October 1957			1 October 1957 to 23 October 1957			23 October 1957 to 10 January 1958			10 January 1958 to 7 March 1958			7 March 1958 to 30 November 1958			Total Stake Displacement			
Stake	(212 Days)			(22 days)			(79 days)			(56 days)			(268 Days)			Total Distance (m)	Mean Direction	Number of Days	Rate of Movement (m/day)
	Dist. (m)	Direction	Rate m/day	Dist. (m)	Direction	Rate m/day	Dist. (m)	Direction	Rate m/day	Dist. (m)	Direction	Rate m/day	Dist. (m)	Direction	Rate m/day				
1	0.22	116°24'	0.001	0.22	26°24'	0.01	0.14	135°0'	0.002	2.9	54°47'	0.05	0.98	-135°0'	0.004	1.2	70°1'	637	0.002
2	---	---	---	0.3	-90°0'	0.014	---	---	---	---	---	---	---	---	---	0.3	-90°0'	22	0.014
4	13.1	36°0'	0.06	1.6	-21°48'	0.07	4.9	34°20'	0.06	---	---	---	---	---	---	18.8	30°39'	313	0.060
4A	---	---	---	---	---	---	---	---	---	---	---	---	2.2	108°26'	0.008	2.2	108°26'	268	0.008
5	55.5	34°43'	0.26	5.5	27°57'	0.25	19.7	33°37'	0.25	14.9	42°16'	0.27	64.8	31°02'	0.24	160.1	33°33'	637	0.25
6	76.3	29°47'	0.36	7.9	26°14'	0.36	27.9	27°56'	0.35	19.6	40°15'	0.35	91.7	26°25'	0.34	222.8	28°58'	637	0.35
8	115.7	26°33'	0.54	12.7	4°30'	0.58	42.2	27°03'	0.53	37.3	48°34'	0.67	142.0	15°56'	0.53	340.4	23°29'	637	0.53
8A	143.8	23°05'	0.68	14.8	10°29'	0.67	52.9	22°04'	0.67	37.9	27°27'	0.68	---	---	---	249.1	22°47'	369	0.67
8B	---	---	---	---	---	---	86.9	19°21'	1.10	62.9	25°50'	1.12	288.5	11°16'	1.08	436.3	14°57'	403	1.08
9	354.0	17°34'	1.67	37.1	8°4'	1.69	133.3	18°57'	1.69	95.3	24°41'	1.70	454.9	13°06'	1.70	1072.3	16°09'	637	1.68
10A	---	---	---	---	---	---	155.4	15°52'	1.97	110.4	32°50'	1.97	553.0	8°56'	2.06	1268.4	14°12'	637	1.99
10B	---	---	---	43.8	12°48'	1.99	154.6	14°51'	1.96	---	---	---	---	---	---	198.3	14°24'	101	1.96
11	---	---	---	---	---	---	164.2	13°12'	2.08	111.6	36°53'	1.99	559.8	6°05'	2.24	856.5	11°16'	403	2.12

Figure 37.--Velocity and elevation profiles of northeast side of Vanderford Glacier.

<u>Stake</u>	<u>Divergence from Axial Line</u>
11	0°00'
10A	2°56'
10B	3°08'
9	4°41'
8A	11°31'
8B	3°41'
7	12°13'
6	17°42'
5	22°17'
4	19°23'

Between Stakes 8A and 8B there is a change in movement direction of nearly eight degrees, whereas between Stakes 11 and 8B the maximum change between adjacent stakes is less than three degrees, and between States 8A and 4 the maximum change between adjacent states is 5 1/2 degrees (Stakes 7 and 6). Also there is a marked change in the velocity between 8A and 8B although these points are not greatly separated. Thus in the eastern part of the glacier two sections can be recognized which exhibit different movement characteristics. Probably, the zone between 8A and 8B is the boundary between the grounded and freely floating ice.

Comparison of the rates of movement during the five time intervals between 3 March 1957 and 30 November 1958, shows that there is no distinct seasonal variation of velocity.

Volume of ice discharge

The area of ice passing a given cross section has been determined by plotting to scale, a profile from the side to the middle of the ice stream, a distance of six kilometers. The vertical lines in Figure 37 represents the surface movement per day at the various markers drawn to the same scale as that used in plotting the position of the markers. The velocity in the middle of the glacier is here considered to be the same as at Stake 11, 765 m/yr, although it may be greater perhaps as much as 900 m/yr. The area under the connected end points represents a surface movement past the initial line of stakes of 3.63 km^2 .

Assuming that the movement profile on the southwest side of the glacier is the mirror image of that on the northeast side, the area of ice passing a fixed transverse line of the glacier is 7.26 square kilometers per year. Since the average position of the glacier terminus remains unchanged over a period of years, the average annual discharge area of ice must also be 7.26 square kilometers.

The thickness of the ice was not measured because neither seismic nor gravity equipment was available. However, the glacier is floating and an estimate can be made of its thickness from its height above sea level. The elevation of the glacier at each of the markers was determined during each survey; the average values for the six surveys are given in Table 29 and are plotted in Figure 37. In selecting

TABLE 29.--Average Elevation of Stakes above
Mean Sea Level

<u>Stake</u>	<u>Meters</u>
1	49.7
2	38.5
4	34.6
4A	37.2
5	31.0
6	40.9
7	39.5
8A	42.1
8B	43.7
9	56.4
10A	55.5
10B	56.9
11	76.8

sites for the movement markers more high than low areas were chosen so that the elevation profile in Figure 37 is more nearly a maximum elevation profile.

For the calculation of the volume of ice discharge the glacier is considered to be a floating body, even though some evidence suggests that it may be grounded as far out as Stake 8A. Similarly it is assumed that the velocity does not vary with depth. This is true in the floating section, but for the grounded section errors may arise.

However, since the velocity is greatest in the floating section errors in the figure for total discharge cannot be great.

If at each site the elevation is a result of the buoyancy of the surrounding block, then the thickness of each block multiplied by the area of ice transported by each block cross section gives the volume of ice transported through each. The total volume is the sum of ice transported by the blocks which is 4.66 cubic kilometers of ice per year. Assuming an ice density of 0.9 gm cm^{-3} , this is 4.19×10^9 metric tons per year, which melts to produce 4.19 cubic kilometers of water.

Waves on the glacier surface

The surface of the glacier consists of a series of large, irregular wave crests and troughs which are not continuous over the width of the glacier, Figures 35 and 38. Angular measurements from the baseline to three prominent crests were made during five of the surveys. Both horizontal and vertical angles, measured from the end of the baseline (Point B), are given in Table 30.

The exact distance from the baseline to the crest was not known but these crests constituted the skyline and their position was approximately the same as the furthest movement state, No. 11. Assuming that the distance from the baseline to Crest #1 was 5.2 kilometers at the time of the first set

Figure 38.--Vanderford Glacier from Haupt Nunatak. Arrows point to wave crests on the glacier. Ice motion is from left to right.

TABLE 30.--Horizontal angles between Haupt Nunatak Point A and wave crests on the Vanderford Glacier

Date	Wave Crest	Horizontal Angle	Vertical Angle
3 March 1957	1	98°36'	+28'
	2	114°45'	+25'
	3	131°01'	+17'
23 October 1957	1	102°56'	+28'
	2	118°58'	+20'
	3	133°19'	+13'
10 January 1958	1	104°25'	+30'
	2	120°22'	+18'
	3	134°20'	+13'
6-7 March 1958	1	105°42'	+28'
	2	122°40'	+18'
	3	135°04'	+12'
30 November 1958	1	110°12'	+28'
	2	126°53'	+17.5'
	3	138°20.5'	+11.5'

of measurements, on 3 March 1957, and that the movement direction was similar to Stake 11, then the resultant lengths of the two waves are 1.45 kilometers and 1.76 kilometers for an average wave length of 1.60 kilometers. The amplitude of these waves is estimated to be 10 meters.

The velocities of the wave crests for the period 3 March 1957 to 30 November 1958 were as follows:

<u>Crest</u>	<u>Velocity, m/day</u>
1	1.67
2	1.99
3	1.55

These values are similar to the rates of glacier movement as determined by stake displacement (2.1 m/day at Stake 11).

Crest movement rates can only be approximated as the exact spot on the crest which is sighted each time is the highest area and as the glacier moves past the observer a different portion of the wave is in view. The movement rates determined, however, suggest that the waves are moving down glacier at the same rate as the glacier itself. These waves are thus stationary relative to the glacier.

The wave crests and troughs probably represent thick and thin ice. This variation in ice thickness could not have been developed in the environment near the terminus and thus the waves must be formed up glacier. The manner in which they are formed is not known but some possibilities are suggested. As the ice flows down from the inland ice to this channel there should be no reason for a wave to form because of variation in accumulation or movement. However, as the ice begins to float it is strained by tides, and the water temperature varies from winter to summer; so it is subjected to mechanical and thermal stresses which might possibly induce the wave form. The magnitude of these stresses is not known and no rigorous explanation of wave formation can be proposed. An annual cycle of wave formation would seem logical but the wave lengths measured are about two times the annual movement.

It is possible that the waves are annual in nature and are formed at the floatation line and the wave length

increases towards the terminus by tensional thinning of the ice stream.

Strain Net at S-2

Measurement of the stake net

A stake net was established at S-2 in order to study the strain of the ice sheet surface. Between 12 and 15 March 1957 a set of 12 stakes, A through L, were emplaced in a polygonal pattern covering about 27 square km. On 16 March the baseline AB was measured three times with an Invar tape and during the period 16-20 March all points of the pattern were occupied and angles of the component triangles were measured. A 30-second transit was used for this work.

In January of 1959 the stake net was remeasured by Hollin. The baseline was measured a total of three times on 8 and 9 January and the triangulation was done on 10, 15, and 17 January. The instrument used for these measurements was a Wild T-2 theodolite which can be read to 10 seconds. The interval between the first and the second survey was 666 days. The results of these surveys are given in Figures 39 and 40 and in Appendix III.

Strain of stake net

Absolute movement of the ice sheet at S-2 has not been measured as there are no nunataks in the vicinity from which the network of stakes is visible to compare any dis-

Figure 39.--S-2 Strain net triangulation - 16-20 March 1957.

Figure 40.--S-2 Strain net triangulation - 6-17
January 1959.

placement. Astronomical fixes are not sufficiently precise to record the small displacements.

In calculating the deformation or strain of the geometric pattern it has been assumed that the entire pattern has moved down-slope as a unit and in so doing the baseline AB has remained parallel to its original position. Coordinates for all points were calculated for the 1957 survey with Point B as the reference point and Line AB oriented due north. The 1959 survey has been compared to the original survey by regarding Point B as fixed and extending the baseline AB 0.33 m to the north.

Comparing the two sets of coordinates shows the change of length of the 25 lines which make up the pattern. Some lines show a negative strain and others a positive strain, depending on their orientation. A plot of these strains and orientations are given in Figure 41, and the values are given in Appendix III.

The strains vary from a maximum of $+38 \times 10^{-5} \text{ year}^{-1}$ to a minimum of $-240 \times 10^{-5} \text{ year}^{-1}$. One value of $-144 \times 10^{-5} \text{ year}^{-1}$ for the line AJ seems to be in error. It is the only value out of 25 that lies outside the extremes noted. In Figure 41 the plot of the strains against azimuth shows a marked variation, with positive strains occurring near 18° and the negative strains near 90° , suggesting a sinusoidal variation of strain with azimuth.

Figure 41.--Strain versus azimuth of lines in S-2 strain net.

At S-2 then there is compressive strain downslope of about $-24 \times 10^{-5} \text{ year}^{-1}$ and an extensive strain perpendicular to the slope of about $+35 \times 10^{-5} \text{ year}^{-1}$, these two principal strains being 90° apart. On an ideal ice sheet both the longitudinal and transverse strains at such a position as S-2 should be extensive. The strain pattern at S-2 then suggests that the forward motion of the ice is being blocked and the ice is being forced to flow around the obstruction, the Windmill Islands, producing compressive east-west strain and extensive north-south strain.

Similar strains studies have been made by Crary and Swithinbank. Their measurements, however, were made on ice shelves and record only extensive strains. Crary obtained values of 129×10^{-5} and $81 \times 10^{-5} \text{ year}^{-1}$ for the two principal strains 90° apart and Swithinbank recorded 138×10^{-5} and $55 \times 10^{-5} \text{ year}^{-1}$ (Crary, 1961, p. 873). In both cases the maximum strain value was normal to the direction of flow. No attempt is being made to compare the ice shelf mechanics of deformation to what is occurring on the ice sheet at S-2 but rather to point out that the difference in strain rates on the ice shelves and on the ice sheet is not great.

Recently reported work on the Ross Ice Shelf near McMurdo Sound by Stuart and Bull (1963, p. 406) suggest compressive strain (parallel to the direction of movement) of $-760 \times 10^{-5} \text{ year}^{-1}$. This area is certainly anomalous as far as

the large ice shelves are concerned and the peculiar ridge and trough system, normal to the direction of ice flow, is a resultant of this compressive strain, this itself is due to the ice moving up against Ross Island.

The area of the polygonal net at S-2 at the first survey was 27 square kilometers, 6.0 km in an east-west direction (downslope) and 4.5 km in a north-south direction (normal to the slope). The compressive strain E-W is $-24 \times 10^{-5} \text{ year}^{-1}$ which reduces the 6.0 km by 1.44 m in one year. The extensive strain is $+35 \times 10^{-5}$ which increases the 4.5 km by 1.37 m. Thus the original area of 27 square km is increased by only 3 square m in one year, a negligible amount. Thus the accumulation at S-2 is not compensated by spreading of the ice sheet but by the motion of the ice sheet. However, it is not possible to calculate the forward movement of the ice sheet.

Ice Abutting the Windmill Islands

For a distance of 30 km to the north of the Vanderford Glacier the continental ice sheet abuts the low lying Windmill Islands. The only area where any ice flows into the sea is in the small Peterson Glacier between Odbert and Browning Islands. This glacier is heavily crevassed but does not take on the appearance of an ice stream. The glacier is more a result of the immediate coast irregularity and is not channeling large quantities of ice to the sea.

A series of measurements was taken at a locality called Grinnell Glacier to determine the amount of ice, if any, being discharged between Clark and Bailey Islands. Six stakes were set in the ice and measured periodically during 1957 and 1958. No movement was recorded.

Measurement of the motion of the ice at the shear moraine just inland of the Grinnell Glacier in 1958 (Hollin, et al., 1961, p. 43) gave the following rates:

<u>Point</u>	<u>m/year</u>
LB	0.39
UB	0.80
M1	1.79
M4	0.54
M5	0.98
A	0.83

This ice is barely moving and this forward motion is coupled with an upward shear so that this ice is probably being dissipated by surface ablation.

The ice mass just inland of the islands is slow moving and the ice sheet is flowing to the north and south of the islands to discharge its ice.

Cape Folger

North of the Windmill Islands the ice front is unobstructed as it moves into the sea. One prominent ice cape, Cape Folger, is readily visible from Wilkes base and the movement of this cape was measured by Tressler and Eyres from March to December of 1958 (Tressler, 1960, p. 11).

The average velocity of Cape Folger for this period of investigation was 14.6 cm/day or 53.3 m/year.

Cape Folger is morphologically similar to the remainder of the ice front north and east to Cape Poinsett, a length of ice front of 75 km. It is reasonable to assume that the same velocity can be applied to this entire stretch of coastline.

Conclusions

The terminus of the ice sheet along the Budd Coast consists of ice streams, ice front, and ice terminating on land. From the studies of ice movement made in this area the amount of ice discharge can be estimated. The coastline from the southwest side of the Vanderford Glacier to Cape Poinsett is 167 km long. The rate of movement of the Peterson Glacier was not measured but for the summary of ice discharge it is assumed to be moving at least twice as fast as the ice front, or 30 cm per day. This is a minimum value. By summing the discharge of the ice stream and the ice front, the amount of ice discharged along the coast is 6.23 km^3 per year, Table 31.

Using a density of 0.9 gm cm^{-3} , the yearly ice discharge of 6.23 km^3 is equivalent to 5.6 km^3 of water.

TABLE 31.--Ice discharge along the Budd Coast

	Length of Coast (km)	Ice Thickness (km)	Ice Velocity (km/yr)	Ice Discharge (km ³ /yr)
Vanderford Glacier	12	--	--	4.66
Peterson Glacier	6	0.25	0.10	0.15
Ice Front	129	0.22	0.05	1.42
Rock Outcrop	20	--	--	--
	167	--	--	6.23

REGIME

The mass balance of a glacier is the algebraic sum of incoming and outgoing ice. The mass balance of cirque and valley glaciers, which have definite boundaries, can be treated rigorously as present photogrammetric mapping can be used to determine changes in ice volume. The regime of ice sheets, on the other hand, is more difficult to determine not only because of size but the lack of methods to measure changes in ice elevation of the interior, and the general paucity of data on ice discharge along thousands of kilometers of coastline. However, estimates of the mass balance of an ice sheet can be made from known accumulation data and averages of the velocity of ice discharge at the periphery. More difficult, however, is the determination of the regime of a small coastal section of an ice sheet. The main difficulty is the unknown quantity of ice moving from the inland into this sector.

The Budd Coast section considered here is bounded by an east-west line 120 km long from the coast and passing through S-2, a north-south line 105 km long from Cape Poinsett, and the coastline, 155 km long, from Cape Poinsett to the intersection of the east-west line with the coast, Figure 42. The area thus delimited is 9,400 square

Figure 42.--Sector of Budd Coast used for regime calculations.

kilometers (measured by planimeter). The coastline considered here excludes the Vanderford Glacier.

Surface ablation near the coast is not important in this area. Budd (1963, p. 34) has summarized this in the following statement:

The local Wilkes area, below 380 m, has experienced negligible net accumulation since 1957, with values for individual years ranging from +6 cm of water (1961) to -3 cm of water (1960).

Thus the area to be considered here is essentially all in the accumulation zone. The accumulation over the area was determined by stakes and snow pits and ranged from 7.9 to 15.9 gm cm⁻² per year.

The ice discharge at the coast amounts to the equivalent of 1.41 km³ of water per year and this would be balanced by an accumulation of 15 gm cm⁻²yr⁻¹ over the 9,400 square kilometers. Thus the ice discharge is just adequate to compensate for the annual accumulation; this suggests that there is little inland ice flow into this area. Jewell (1962) reports that south of S-2 there is a depression in the ice sheet, aligned northwest. This is possibly caused by the Vanderford ice stream. This depression indicates that no ice can be flowing across this area to the vicinity of S-2. Contour lines are perpendicular to the north-south boundary and no ice is flowing into the area along this line.

The mass balance of this area is principally dependent on snow accumulation and not the flow of inland ice; thus

fluctuations in the ice mass are a reflection of change in accumulation.

The data from the deep pit indicate that the accumulation for the last 174 years averaged 13.3 gm cm^{-2} . If this value is applied over the whole sector there would be an accumulation of 1.25 km^3 of water. Assuming that the velocity of ice discharge has remained the same over this period this would mean a deficit or excess of ablation over accumulation of 0.16 km^3 of water per year. Thus this sector of the ice sheet is probably thinning.

Evidence from the vicinity of the Windmill Islands suggest that the ice of the Budd Coast is thinning. Shear moraines or Thule-Baffin type moraines are formed at the terminus of thinning ice sheets and these are forming along the Windmill Islands. These "shears" are forming parallel to the coast and new shears are developing inland. Snowdrift-ice fields formed throughout the islands are slowly disappearing as shown by a lichen trimline, Figure 43. This suggests an amelioration of the local climate.

As the ice sheet in the Budd Coast area is maintained by local accumulation the thinning of the ice sheet must be a result of low accumulation over a prolonged period.

Figure 43.--Lichen trimline on boulder, Clark
Penisular, Windmill Islands.

THE FORMER EXTENT OF THE ICE SHEET

Expansion of the Ice Sheet

The terminal configuration of the ice sheet along the Budd Coast is presently controlled by the relative relief of the bedrock. At an earlier time of thicker ice, the entire Windmill Islands group and the Balaena Islands to the north were completely overridden by the ice sheet, as shown by striae, grooves, lunoid markings, polished surfaces, erratic blocks, and ground moraine. Whether or not this ice coverage has been repeated is unknown. No evidence has been discovered on the islands to indicate cyclic glaciation.

Ice movement across the Windmill Islands was in an arc of 30° from S 85° W to N 60° W. In some instances two sets of striae occur on the same outcrop, Figure 44, but the change in direction of ice motion was probably caused by changes in ice thickness and subsequent bedrock control of the movement direction and is not unequivocal evidence of successive glaciation.

In the Balaena Islets a glacial groove indicates that ice motion over the area was N 20° E. This well developed groove is 25 cm wide and 3 m long.

In front of the terminus of the Vanderford Glacier is a deep trough which undoubtedly controlled the over-all ice

Figure 44.--Two sets of striae on Clark Peninsula, Windmill Islands. Arrows show direction of ice movement.

expansion in the Budd Coast area during maximum glaciation. This trough will be discussed in detail; here it is sufficient to say that the movement of ice in the trough was generally toward the north-northwest.

As the ice expanded over the Windmill Islands, the ice first moved westerly to cover the islands. As the ice grew thicker and thicker, the ice of the Vanderford Glacier filled the trough in front of the glacier, forming such a massive ice stream that ice moving over the Windmill Islands was redirected into a more northwesterly direction. Ice moving out between the Windmill Islands and the Balaena Islets encountered relatively shallow water, so the ice could readily become grounded and would therefore build out rapidly to the north-northwest separating the Balaena Islets from the Vanderford ice stream. Thus the ice flowing over the Windmill Islands would have been moving toward the ice stream to the west while the ice flowing over the Balaena Islets would have been moving north-northeasterly.

The Vanderford Submarine Valley

The Vanderford Glacier flows northwest as an ice stream within the continental ice sheet and discharges into the southeast part of Vincennes Bay. An exceptionally deep sounding of the bay in front of the glacier was recorded on a Hydrographic Office chart compiled from data collected during the U.S. Navy Operation Windmill in 1948. This

prompted a more detailed sounding of this area. In January of 1958 the captain of the icebreaker U.S.S. Staten Island was persuaded to make several sounding runs in this bay area. A bathymetric chart prepared from these data is shown in Figure 45.

A submarine valley can be traced from the front of the Vanderford Glacier north-northwest and then west a total distance of 25 km. The axis of the valley is shown in the figure by a dashed line. Study of available Hydrographic Office charts and preliminary work sheets of soundings made by the U.S. Navy ships operating in the area during the IGY and IGC fails to show any distinct continuation of the valley northward across the continental shelf. However, too few data are available to make any definite statement as to the termination or continuation of the valley to the north. Study of the aerial photograph, Figure 35, suggests that the Vanderford Glacier is afloat from its terminus to at least 35 km inland. Further evidence of the inland extension of the valley has been provided by Australian seismologists who have recorded a reflection from the ice-bedrock interface at 2440 m below sea level at a site 130 km southeast of the glacier terminus (Jewell, 1962).

Profiles of the valley are shown in Figure 46. The longitudinal profile shows the water depths from the glacier terminus in the south to the known extent in the north. The greatest water depth is 2287 m immediately in

Figure 45.--Bathymetric chart of Vincennes Bay showing deep valley in front of Vanderford Glacier.

Figure 46.--Cross profiles of Vanderford submarine valley. No vertical exaggeration.

front of the glacier. As the valley is traced north and west, a distance of 25 km, the depth decreases to 1829 m; thus the valley has a gradient of just over 1° and is sloping landward. The cross profiles show that the valley averages about 12 kilometers wide. Note that there is no vertical exaggeration in these profiles. Profile 1 is 16.2 km long; the average slope of the northeast wall is 26° , the slope of the southwest wall is 16° , the relief is 1,944 m and the water depth is 2,057 m. Profile 2 is 23.8 km long, the slope of the northeast wall is 10° , the average slope of the southwest wall is 27° and one part is nearly 45° ; the relief is 2,444 m and the water depth is 2,149 m. Profile 3 is 10.5 km long, the slope of the northwest wall is 16° and the slope of the southwest wall is 25° , the relief is 1,955 m and the water depth is 2,287 m. These profiles are compared in Table 32. The valley is asymmetrical with the steeper slope on the southwest side in profiles 2 and 3 and on the northeast side in profile 1. Profiles 2 and 3 are not at right angles to the valley axis so that the slopes are not maximum slopes.

This deep valley can be compared to three valley types (1) a subaerial canyon, (2) a submarine canyon, and (3) a fjord. Cross profile 2 of the Vanderford valley is compared in Figure 47 with transverse profiles of the Grand Canyon, the Monterey submarine canyon, and the Sogne Fjord of Norway. This graphic comparison shows the distinct

TABLE 32.--Comparison of Cross Profiles of Vanderford Submarine Valley

	Profile		
	1	2	3
Length of profile (km)	16.2	23.8	10.5
Slope of NE wall (degrees)	26°	10°	16°
Slope of SW wall (degrees)	16°	27°	25°
Relief (m)	1,944	2,444	1,955
Greatest water depth (m)	2,057	2,149	2,287

similarity between the Vanderford valley and the Sogne Fjord; they are nearly the same width, are extremely deep, and have relatively smooth U-shape profiles. The two canyons, on the other hand, although about as deep, are nearly twice as wide and have comparatively rough, V-shape profiles.

A subaerial canyon has a profile which is V-shaped, not U-shaped, and it often has an asymmetrical cross profile caused by undercut and slip-off slopes, structural knobs, homoclinal shifting, and climatic differences on the two sides of the valley (Thornbury, 1954, pp. 111-112) in addition to a longitudinal profile that has a seaward rather than a landward gradient. The cross profiles are also usually irregular. Thus, the Vanderford valley is not principally a subaerially produced, subsequently drowned canyon.

Figure 47.--Comparison of cross profiles: Vanderford submarine valley, Grand Canyon, Monterey submarine canyon, and Sogne Fjord.

Fjords, however, are U-shaped, have relatively steep and straight walls, and the longitudinal profile is undulating with the deepest parts frequently in the inner portions. This describes the Vanderford valley. Fjords are generally characterized by high, steep walls on both sides of the valley; however, here there are only some islands and nunataks which rise up a bare 60 to 90 m above sea level. In that valley walls do not rise appreciably above sea level, this valley could be called a drowned glacial trough, the term used for fjords when they extend onto the continental shelf.

The slope of the valley, its proximity to an active ice sheet, and the channelling of ice by the sea level portion of the valley are convincing evidence of the origin and role of this valley. This fjord is of exceptional vertical dimensions and may also prove to be unusually long. In Table 33 depths of fjords from different parts of the world are compared. This table is modified after Peacock (1935, p. 669).

The Vanderford Fjord is 837 meters deeper than the Northwest Fjord in Greenland, which is presently considered the world's deepest fjord.

TABLE 33.--Greatest Known Fjord Depths (m)

(Values given are depths of water; depths
to bedrock may be greater)

In British Columbia	780	Finlayson Channel
In Alaska	878	Outer part of Chatham Strait
In Europe	1,210	Sogne Fjord, Norway
In South America	1,288	Messier Channel, Patagonia
In Greenland	1,450	Northwest Fjord, Scoresby Sound
In Antarctica	2,287	Vanderford Fjord

Extent of the Ice Cover

The striae and grooves on the bedrock attest to ice movement over the islands, and the Vanderford fjord is evidence for the considerable thickness of the ice cover. Voronov (1960, Yevteyev (1961), and Hollin (1962), have all discussed the previous extent of the Antarctic ice sheet. Their conclusion is that because there is no ablation area, sea level is the limiting factor in the size of a grounded ice sheet like Antarctic which is surrounded by water. Hollin has shown that the maximum altitude of the Antarctic ice sheet is very little affected by substantial changes in accumulation rate and air temperature, so that the profile of the ice sheet is controlled almost entirely by the flow law of ice. The equilibrium profile of an ice sheet is

always of the same form (the over-all profile is elliptical but the margins are more nearly parabolic) so that the mean height and hence the mass of the ice sheet depends on its radius. Thus a lowering of sea level allows the ice sheet to extent and increase its mass whereas a rising sea level reduces the radius and thus the mass of the ice sheet. The estimates of the mean northward extension of the grounded Antarctic ice during minimum sea level are as follows:

Yevteyev	100 km
Voronov	190 km
Hollin	90 km

A detailed bathymetric map is required before more reliable estimates can be made for a particular area. The major difference between Hollin and Voronov is in the assumption of the amount of lowering of sea level. Voronov proposes a lowering of 300-500 m while Hollin suggests 150 m. The evidence and reasoning presented by Hollin is indeed more convincing and is in accord with the conclusions of Ewing et al. (1960), and Fairbridge (1961).

Soundings and bottom sampling made in Vincennes Bay and in the area due north provide enough data to permit a general profile of the bottom topography (U.S. Navy Hydrographic Office publication, TR-29, 1957 and TR-33, 1956, and Goodell et al., 1962). Figure 48 shows the bottom profile from Wilkes Station, at $66^{\circ}16'$ lat. due north to $64^{\circ}18'$ lat.

Figure 48.--Maximum glaciation of the Windmill Islands.

Superimposed on this bottom profile, Figure 48, are certain conditions which probably existed during maximum glaciation. It is assumed that sea level was 150 meters lower than at present and that the terminus of the grounded ice sheet was 220 meters thick. Two soundings were taken by hand line at the base of the ice front during a two-day trip to Cape Poinsett in December, 1957. The soundings were taken at latitude $65^{\circ}30'$, longitude 113° and showed water depths of 194 and 198 meters. The ice cliffs in this area where the grounded ice sheet reached the sea averaged 20 meters.

To determine the northerly extent of the grounded ice sheet during maximum glaciation we assume that sea level was 150 m lower than today and that the ice sheet remained grounded until it reached water 200 m deep. From Figure 48 this point can be found graphically. The profile of the ice sheet from this point, the terminus, inland could be calculated from the parabolic equation

$$h = 4.7 \sqrt{d} \quad (8)$$

where d is the distance in meters from the edge of the ice sheet and h is the height or thickness, of the ice in meters. This equation fits the observed profile from Mirny to Pioneerskaya and is the profile presented by Nye (1952) of a perfectly plastic ice sheet with a yield stress of 1.0 bar (Hollin, 1962, p. 178).

This profile is drawn from the ice sheet terminus 60 m north of the site of Wilkes Station. During this period of maximum glaciation, the thickness of the ice cover at Clark Peninsula was at least 750 m and that at the site of the present terminus of the Vanderford Glacier, 25 km to the south of Clark Peninsula, 950 m. These figures are thicknesses of ice above present sea level.

The seismic profile from S-2 due south shown in Figure 49 is modified from Jewell (1962). The depression in the bedrock is the inland extension of the Vanderford Fjord. Note that the ice thickness on the north and south sides of the "fjord" are 1533 m and 1402 m respectively, not too dissimilar from the calculated ice thickness for the vicinity of the Vanderford terminus (1300 m). We have then a profile of an ice sheet controlled by the physical properties of the ice and the position of the terminus determined by sea level; inland the bedrock relief is completely filled with ice no matter how deep the valley. There is certainly some surface expression of the sub-glacial topography but it does not influence the over-all profile.

The Vanderford Fjord then was completely filled with ice during maximum glaciation. This fjord may have been deepened or otherwise modified during this glaciation.

Figure 49.--Seismic profile from S-2 southward, showing bedrock topography. From Jewell (1962).

APPENDIX I

METEOROLOGICAL DATA

Temperature and Wind Speed at the Main Base
 4 March 1957 to 28 January 1958
 Election: 15 meters above sea level

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
March				
4	3.0	1.1	5.5	7.2
5	4.6	1.6	7.8	14.3
6	0.8	+1.6	2.8	20.5
7	1.9	0.5	3.9	9.9
8	1.8	+0.5	3.3	6.9
9	1.4	+1.6	3.9	5.1
10	6.0	4.4	8.3	6.7
11	4.7	2.8	7.2	6.7
12	3.0	0.5	6.1	2.8
13	5.3	4.4	8.9	4.6
14	6.3	3.9	8.3	8.4
15	7.6	4.4	9.4	6.1
16	6.9	2.8	10.0	7.9
17	2.4	1.1	5.5	16.1
18	3.0	1.1	6.6	5.9
19	5.3	4.4	7.2	23.3
20	8.2	7.2	10.0	6.4
21	7.8	4.4	11.1	18.1
22	3.8	1.1	5.5	24.5
23	3.8	1.1	6.1	6.2
24	2.4	+0.5	5.5	2.3
25	3.5	2.2	6.1	7.6
26	4.1	1.1	7.2	11.8
27	3.9	2.8	8.3	7.1
28	7.5	6.1	10.5	8.9
29	7.8	4.4	10.5	24.6
30	5.8	2.2	8.9	14.9
31	2.5	+0.5	5.0	15.9
April				
1	3.5	2.2	6.6	5.7
2	5.0	3.3	6.6	30.5
3	1.0	+1.1	5.0	20.6
4	1.1	+2.2	6.6	11.5
5	7.9	5.5	11.1	12.5
6	5.8	4.4	8.9	6.9
7	6.0	3.3	9.4	5.5

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
April (continued)				
8	7.9	6.1	10.0	10.2
9	8.0	6.1	11.1	4.6
10	13.0	10.0	16.1	4.9
11	10.3	8.9	14.4	6.6
12	11.4	9.4	16.1	7.0
13	12.8	6.6	18.9	14.2
14	12.4	11.6	14.4	4.3
15	11.6	5.5	15.5	18.4
16	3.9	+0.5	6.6	30.2
17	2.1	5.5	1.6	33.5
18	0.8	0.0	1.6	40.8
19	1.0	0.0	1.6	16.7
20	0.4	+0.5	3.3	21.8
21	3.5	1.1	7.2	10.4
22	5.0	1.6	7.2	13.8
23	6.0	5.0	7.2	9.9
24	2.4	0.0	6.1	32.9
25	3.0	1.6	5.5	10.6
26	8.3	4.4	12.8	3.7
27	10.3	8.3	15.0	7.0
28	13.9	10.0	17.2	9.8
29	6.4	5.0	13.3	42.9
30	5.7	3.3	8.3	21.4
May				
1	7.8	5.5	9.4	17.7
2	7.8	5.5	12.2	12.9
3	9.9	5.0	16.1	6.3
4	16.9	14.4	20.5	7.6
5	13.8	9.4	20.5	6.2
6	10.3	8.3	12.2	4.4
7	11.5	10.5	16.1	6.0
8	16.9	13.3	21.1	5.0
9	8.9	5.0	21.1	22.4
10	4.7	3.3	6.6	24.5
11	7.6	3.9	12.8	8.2
12	16.6	11.6	22.8	5.0
13	21.1	17.2	25.5	1.2
14	20.6	16.1	22.2	5.5
15	21.2	18.3	25.5	6.0
16	19.5	17.8	25.5	7.3
17	12.6	9.4	18.3	4.0
18	11.6	9.4	13.9	12.2
19	7.8	5.0	10.5	30.9
20	11.8	9.4	16.1	10.6

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
May (continued)				
21	17.5	12.2	25.0	6.9
22	19.7	11.6	25.0	11.4
23	10.4	7.8	13.9	2.0
24	9.7	3.9	17.8	29.1
25	13.9	10.0	17.8	16.4
26	15.5	10.5	21.1	16.1
27	18.4	6.6	21.1	24.0
28	4.7	1.1	10.0	48.8
29	1.5	+2.2	4.4	36.1
30	0.1	+3.9	2.8	7.3
31	+0.3	+5.5	6.6	6.0
June				
1	12.8	2.2	14.4	22.8
2	17.4	9.4	21.6	33.4
3	8.0	6.1	12.8	6.7
4	8.6	6.1	11.1	6.9
5	10.4	6.6	14.4	5.3
6	14.9	12.2	18.3	5.7
7	19.8	15.5	23.9	20.1
8	22.3	18.9	24.4	19.3
9	21.5	20.5	23.3	5.2
10	22.1	20.0	25.5	6.2
11	24.8	23.3	26.6	1.9
12	26.4	24.4	27.2	0.9
13	22.3	20.5	25.5	5.9
14	25.3	21.6	28.3	3.6
15	28.5	26.1	30.5	4.4
16	21.5	14.4	29.4	6.6
17	16.6	10.5	20.0	6.6
18	19.7	17.8	21.6	4.2
19	20.0	16.1	22.8	1.8
20	15.1	11.6	22.2	2.7
21	12.1	10.5	14.4	1.6
22	11.6	3.9	17.8	12.1
23	3.2	1.6	6.1	32.5
24	7.1	+1.6	12.8	4.2
25	11.4	6.1	13.9	4.0
26	13.6	8.9	20.0	4.9
27	19.5	18.3	24.4	5.6
28	12.9	20.0	26.6	4.4
29	24.8	22.2	27.8	3.8
30	26.5	22.8	29.4	7.9

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
July				
1	22.9	15.0	27.8	2.9
2	17.5	12.8	24.4	4.0
3	20.6	16.6	22.8	1.2
4	16.5	15.5	21.1	5.5
5	18.4	15.5	23.9	7.9
6	24.0	19.4	28.3	7.0
7	16.1	10.5	25.0	7.8
8	10.1	4.4	13.9	21.6
9	10.4	3.9	17.2	13.1
10	14.3	11.1	19.4	3.9
11	13.0	11.1	17.2	4.0
12	16.4	12.8	20.5	6.8
13	16.3	14.4	24.4	4.4
14	22.5	10.0	26.6	3.9
15	10.5	9.4	20.0	58.5
16	9.4	6.6	12.8	4.7
17	12.1	6.6	18.9	4.2
18	19.7	13.3	24.4	16.9
19	20.0	13.3	28.3	16.8
20	23.6	18.9	30.0	11.9
21	24.5	21.1	26.1	5.2
22	23.6	21.1	28.3	7.9
23	24.5	20.5	30.5	3.4
24	25.0	21.1	32.8	3.3
25	17.5	6.6	26.1	9.2
26	12.1	7.2	23.3	4.3
27	17.1	10.5	21.6	29.6
28	18.4	14.4	21.6	12.4
29	20.3	15.5	24.4	5.7
30	17.9	15.5	21.6	9.2
31	13.0	10.5	21.1	10.1
August				
1	18.7	12.8	23.3	13.7
2	7.5	3.9	12.8	11.9
3	10.8	7.2	18.3	6.9
4	18.1	14.4	22.8	8.3
5	14.1	8.3	20.2	26.0
6	10.7	5.0	17.2	21.0
7	15.8	13.3	18.9	3.3
8	17.4	13.9	22.2	3.0
9	20.5	13.3	23.9	3.7
10	13.6	12.2	17.2	4.7
11	17.9	12.2	22.8	3.3
12	16.8	12.8	21.6	3.9
13	10.5	3.9	14.4	11.5

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
August (continued)				
14	9.0	5.5	10.5	37.7
15	6.9	3.9	9.4	31.9
16	7.8	4.4	10.5	20.6
17	11.9	8.9	15.0	5.2
18	16.4	12.8	19.4	3.9
19	18.3	16.6	20.0	5.6
20	13.9	9.4	21.1	40.4
21	12.9	9.4	15.5	9.1
22	13.6	10.5	15.5	3.6
23	12.5	8.3	15.0	38.6
24	8.5	4.4	11.1	14.9
25	6.1	3.9	8.3	46.9
26	3.0	2.2	8.3	21.0
27	2.6	0.0	4.4	19.7
28	4.9	1.1	9.4	8.6
29	11.4	7.8	14.4	8.2
30	12.1	8.9	17.8	5.5
31	17.5	12.2	21.5	4.4
September				
1	16.3	10.5	22.2	7.0
2	11.9	8.9	16.6	7.5
3	9.3	5.0	14.4	6.5
4	9.3	3.9	17.2	8.3
5	17.9	8.9	20.5	9.8
6	9.9	8.3	17.8	17.9
7	18.3	16.1	21.6	9.9
8	19.4	14.4	22.2	3.0
9	11.9	6.1	21.1	40.0
10	5.8	0.5	9.4	45.6
11	11.7	1.6	7.2	20.6
12	5.3	3.3	9.4	6.3
13	10.4	5.0	17.8	3.3
14	15.3	10.5	18.9	3.4
15	12.5	5.5	18.9	11.1
16	8.0	6.1	10.0	24.5
17	11.0	8.3	12.8	30.5
18	9.9	6.1	15.5	25.5
19	14.9	12.2	17.8	7.2
20	19.5	15.0	21.6	12.8
21	14.9	13.3	18.3	5.9
22	13.8	10.5	17.8	5.9
23	11.4	9.4	13.3	5.3
24	11.4	8.3	12.8	8.8
25	9.1	7.8	10.5	30.4

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
September (continued)				
26	8.6	5.0	11.1	13.1
27	8.0	5.0	11.1	35.4
28	5.7	3.9	8.3	53.7
29	3.9	0.5	8.9	28.5
30	6.1	4.4	8.9	38.4
October				
1	8.9	4.4	11.6	8.8
2	9.0	4.4	13.3	9.0
3	10.1	4.4	18.9	4.4
4	17.5	13.9	21.6	8.5
5	16.1	11.6	21.1	5.7
6	14.4	7.8	17.8	3.4
7	7.5	2.8	14.4	23.4
8	5.3	2.8	6.6	4.9
9	3.9	+0.5	6.6	20.0
10	4.3	+0.5	6.1	40.0
11	4.3	2.8	5.5	46.8
12	4.9	3.3	6.6	38.3
13	6.0	0.0	11.6	21.9
14	5.3	6.1	15.5	5.9
15	12.1	9.4	15.5	6.6
16	12.1	6.6	15.5	3.6
17	13.8	8.3	12.2	6.5
18	13.9	7.2	13.3	5.2
19	13.9	6.1	15.5	6.2
20	8.3	2.2	13.3	3.3
21	13.6	3.3	13.9	2.3
22	11.6	6.6	16.1	7.5
23	14.9	10.0	19.4	7.8
24	12.4	8.3	19.4	15.7
25	6.3	3.3	11.6	5.7
26	6.9	3.9	9.4	7.0
27	9.4	6.1	13.3	6.9
28	12.1	5.5	16.6	10.8
29	6.6	2.2	12.8	4.3
30	5.3	3.9	11.1	5.0
31	7.4	0.5	11.1	5.0

Date	Temperature, -°C		Mean Wind Speed mph
	Mean	Maximum Minimum	
November			
1	6.0	+0.5	4.7
2	6.1	3.3	16.1
3	6.4	+2.2	18.1
4	3.8	+0.5	7.5
5	2.8	+2.2	3.2
6	7.4	1.6	3.9
7	7.6	2.2	9.1
8	3.2	+1.6	24.5
9	1.6	0.5	28.1
10	3.4	1.1	12.1
11	4.2	2.8	5.2
12	7.2	2.2	4.9
13	4.9	1.6	9.9
14	5.0	0.8	5.9
15	3.8	1.1	3.4
16	5.5	2.2	6.5
17	4.6	1.1	8.1
18	1.3	+2.2	7.6
19	2.4	0.5	9.5
20	4.1	2.2	5.0
21	5.5	1.1	5.2
22	3.3	+1.1	6.6
23	5.2	+1.1	6.6
24	3.3	+1.1	3.6
25	3.3	2.2	3.9
26	3.4	0.8	3.9
27	3.5	1.6	5.5
28	3.3	1.6	6.5
29	3.0	1.6	6.5
30			
December			
1	5.8	0.2	10.4
2	5.1	+2.5	9.1
3	5.8	+5.0	12.5
4	2.8	+2.8	1.7
5	2.8	0.8	6.5
6	1.0	+2.8	7.0
7	0.0	+3.9	14.7
8	0.0	+3.0	5.5
9	+1.1	+3.9	4.3
10	5.1	+2.2	6.0
11	+0.1	+3.9	4.4
12	+0.3	+2.2	4.4
13	+0.1		3.9
14			4.3

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
December (continued)				
15	+0.8	+3.9	1.1	2.7
16	+0.1	+3.3	1.6	1.6
17	+1.5	+5.5	1.1	13.4
18	+2.0	+4.4	1.1	21.9
19	+2.0	+5.5	1.6	21.1
20	+1.5	+6.1	2.2	1.9
21	+1.4	+6.1	3.3	1.9
22	0.0	+3.3	4.4	4.3
23	0.8	+2.2	5.0	4.4
24	0.0	+3.3	3.9	4.7
25	0.1	+1.1	2.2	5.7
26	+1.1	+4.4	2.2	2.3
27	0.1	+4.4	2.8	3.9
28	0.8	+0.5	3.3	13.1
29	0.0	+1.6	1.6	16.2
30	+0.5	+3.3	1.1	3.2
31	+0.4	+2.8	2.2	3.6
January				
1	0.0	+2.2	1.6	3.2
2	0.1	+2.2	2.2	4.0
3	0.0	+1.6	1.1	18.7
4	+0.8	+3.9	0.5	15.4
5	+2.3	+4.4	+0.5	25.8
6	+1.4	+4.3	1.1	4.0
7	+1.1	+2.8	0.5	2.3
8	+0.5	+4.4	1.6	2.9
9	+0.3	+3.9	2.8	4.2
10	0.8	+1.1	3.3	3.4
11	0.7	+3.3	5.0	5.2
12	2.1	+1.6	5.5	6.0
13	2.2	+0.5	3.3	6.3
14	0.4	+1.1	3.3	12.2
15	0.5	+0.5	1.6	15.8
16	+0.1	+1.1	1.6	21.9
17	+1.1	+2.8	1.6	7.8
18	+0.1	+3.9	2.2	4.6
19	0.5	+5.0	2.2	4.3
20	+2.8	+8.3	2.2	3.6
21	1.5	1.1	3.9	6.3
22	0.0	+3.3	2.8	3.4
23	+0.3	+5.0	2.2	3.0
24	+1.2	+4.4	2.8	4.6
25	+0.3	+4.4	3.9	3.7
26	+1.1	+6.1	3.9	7.5

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
January (continued)				
27	2.9	+1.1	5.0	14.4
28	+2.8	+5.0	5.5	8.1
29	+0.8	+2.2	3.3	5.5
30	+0.1	+1.6	4.4	7.5
31	+0.5	+2.8	4.4	7.2

Temperatures at the S-1 Station
23 February 1957 to 27 January 1958
Elevation: 262 meters above sea level

Date	Temperature, -°C		
	Mean	Maximum	Minimum
February			
23	6.1	4.5	7.1
24	6.7	4.5	7.6
25	5.2	3.9	10.9
26	6.8	4.5	10.8
27	7.4	5.3	9.8
28	3.9	1.7	6.3
March			
1	3.1	2.4	4.2
2	3.5	+0.5	8.9
3	7.6	6.3	9.5
4	7.1	4.1	9.5
5	4.3	2.4	6.1
6	3.1	0.5	6.1
7	3.1	1.6	4.4
8	2.8	+0.1	4.4
9	3.9	1.4	5.6
10	6.3	5.0	8.1
11	5.0	3.4	5.5
12	3.5	1.8	5.0
13	4.9	3.3	6.1
14	5.4	4.3	6.1
15	8.8	5.8	11.6
16	8.1	2.8	13.3
17	4.6	2.8	7.3
18	4.1	0.1	7.1
19	6.3	4.9	7.0
27	6.1	3.9	8.6
28	7.4	4.9	7.0
29	8.1	5.0	11.9
April			
2	6.1	3.3	8.8
4	2.8	1.3	8.0
5	10.2	7.7	13.0
6	7.3	6.6	9.5
7	9.0	6.6	13.3
8	12.5	7.4	12.7
9	9.0	7.8	11.6
10	14.2	11.1	19.0

Temperature, -°C

	Mean	Maximum	Minimum
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Date

April (continued)

11	12.0	10.7	13.7
12	11.7	9.0	15.4
13	9.1	6.6	12.4
14	14.1	12.3	16.7
20	2.3	1.9	3.3
21	3.6	1.9	7.7
22	6.9	5.3	8.3
23	6.7	4.0	7.8
24	3.8	3.3	4.6
25	4.1	1.0	11.8
26	12.4	11.0	15.0
27	11.7	10.5	14.9
28	13.9	8.9	16.5

May

1	10.0	8.3	11.5
2	10.5	8.9	12.0
3	11.7	6.8	15.6
4	18.4	15.1	22.2
5	16.9	12.7	21.7
6	12.1	10.9	12.9
7	11.6	8.4	13.6
8	14.4	11.0	20.5
9	7.9	5.8	11.1
10	5.5	5.0	6.0
11	8.1	6.5	12.4
12	17.9	11.6	27.0
13	23.4	18.3	29.6
16	23.4	19.8	27.8
17	15.9	13.8	18.6
18	15.4	12.7	18.0
19	11.8	10.5	12.8
26	18.9	12.4	23.2
31	3.6	1.1	9.5

June

4	22.4	20.0	25.3
5	11.8	18.9	27.8
6	28.3	26.3	31.5
7	28.0	20.5	32.7
8	34.1	31.3	35.5
9	35.1	33.8	37.2
12	16.0	14.6	17.8
13	17.0	11.6	17.8
14			

Temperature, -OC

	Mean	Maximum	Minimum
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Date

June (continued)

15	16.5	12.8	19.4
16	17.5	13.3	19.2
17	10.2	3.9	12.4
18	13.4	2.9	19.0
19	18.0	16.1	21.0
20	18.9	16.7	21.0
21	13.5	8.5	16.2
22	12.5	11.7	15.9
23	11.3	6.5	15.9
24	5.7	4.7	6.4
25	7.7	5.4	10.2
29	25.6	23.1	27.9
31	26.4	24.0	29.4

July

1	26.5	22.6	30.0
2	20.2	16.9	24.3
3	20.9	19.2	23.3
4	23.1	19.5	25.5
5	19.7	19.0	21.1
6	21.3	20.1	24.6
7	25.9	19.4	30.8
8	19.4	13.0	14.4
9	13.5	11.3	15.1
10	13.0	10.5	18.3
14	15.3	13.9	20.5
15	18.1	15.7	20.6
16	17.7	17.2	23.3
17	22.6	12.7	26.1
24	19.3	12.8	26.0

August

1	16.5	14.5	19.9
2	19.0	14.9	21.5
3	11.8	9.9	13.4
4	13.4	12.5	19.6
5	21.5	19.4	23.5
6	19.4	12.8	23.7
9	21.6	19.8	26.6
10	24.5	13.9	28.8
11	15.4	13.9	22.6
12	23.3	21.6	27.7
30	12.7	10.5	17.0
31	15.7	12.9	22.0

Date	Temperature, -°C		
	Mean	Maximum	Minimum
September			
1	17.1	13.5	22.8
2	12.9	10.5	14.6
3	10.7	7.8	14.3
4	9.9	6.0	17.1
5	17.9	11.7	20.0
6	12.4	11.0	17.4
7	18.2	15.4	22.2
8	20.3	14.5	24.5
9	12.5	12.0	13.3
13	12.9	8.3	20.6
14	18.3	14.0	20.0
15	15.6	10.5	13.4
16	12.4	11.5	17.8
22	15.8	11.6	15.0
23	13.4	11.8	15.0
24	14.0	12.8	15.0
26	12.4	10.6	13.0
October			
6	14.0	9.1	17.1
7	9.1	8.7	9.4
8	8.4	6.8	9.7
19	13.6	9.2	20.7
20	12.5	4.0	16.9
21	11.5	4.5	17.2
22	12.7	8.1	18.6
23	17.0	10.4	21.5
24	15.7	11.4	22.1
25	8.6	5.9	11.4
26	9.8	8.3	12.3
27	14.6	10.3	21.8
28	15.6	12.0	22.7
29	10.7	7.0	14.6
30	8.9	6.0	18.4
31	12.2	3.3	19.4
November			
1	10.2	4.4	14.6
2	10.9	8.9	12.8
3	10.0	8.3	12.2
4	5.7	2.4	7.8
5	7.2	1.9	12.3
6	6.3	1.0	15.6
7	11.7	9.9	18.2
8	11.3	2.4	19.0
9	7.0	6.6	7.8

Date	Temperature, -°C		
	Mean	Maximum	Minimum
November (continued)			
10	6.0	5.1	7.8
11	7.4	4.7	8.2
12	6.3	1.3	15.1
13	10.0	4.6	16.4
14	7.2	5.6	8.3
15	6.2	4.1	8.0
16	6.6	+0.2	12.4
17	9.1	3.1	13.1
18	9.1	3.0	13.8
19	8.5	2.4	14.2
20	1.9	+6.7	7.0
21	4.9	2.8	9.0
22	7.3	4.4	11.4
23	10.5	6.5	12.7
24	7.1	3.3	10.1
25	6.3	+0.6	14.4
26	8.4	+2.7	14.5
27	3.6	+2.1	9.4
28	3.9	+2.2	7.6

December

3	3.1	+4.0	7.7
4	0.3	+4.4	7.1
5	4.3	9.0	8.8
6	5.5	2.7	9.4
7	4.0	0.0	7.9
8	3.6	+2.6	9.8
9	2.1	+4.0	7.2
10	0.6	+3.3	7.1
11	0.3	+3.6	7.2
12	1.5	+0.4	7.5
13	9.0	+7.3	9.6
14	1.3	+4.2	6.1
15	0.3	+4.2	6.2
16	0.0	+2.6	2.4
17	0.9	+0.8	2.9
18	0.8	0.2	2.8
19	0.1	+2.0	1.0
20	2.6	+3.6	6.0
21	0.7	7.3	7.1
22	2.0	+3.1	7.3
23	3.1	+0.2	7.8
24	3.2	+1.1	7.9
25	1.9	+2.5	4.1
26	0.8	+5.8	4.3
27	0.0	+2.0	5.8

Date	Temperature, -°C		
	Mean	Maximum	Minimum
December (continued)			
28	2.4	0.9	3.5
29	3.0	2.0	4.0
30	+0.8	4.3	1.9
31	0.3	+4.6	2.1
January			
1	2.1	0.8	3.6
2	1.6	1.2	4.7
3	4.1	2.6	4.6
4	2.4	+0.5	3.5
5	1.1	+0.3	3.8
6	+1.1	+3.9	1.4
7	+0.7	+4.0	1.3
8	1.1	+1.6	5.9
9	3.1	+1.1	6.8
10	3.5	1.4	6.0
11	3.0	1.4	9.3
12	5.3	1.7	9.3
15	3.3	2.1	4.3
16	3.4	2.7	4.3
17	2.0	+0.7	3.9
18	0.6	+5.5	4.5
19	+0.2	+6.0	3.9
20	0.1	--	3.8
21	2.2	+0.1	4.3
22	2.2	+3.5	6.0
23	1.5	--	3.3
24	+0.1	+4.1	4.4
25	1.8	+3.1	5.9
26	1.7	+3.1	7.3
27	5.4	4.0	--

Temperature and Wind Speed at the S-2 Station
 13 March 1957 to 16 January 1958
 Elevation: 1166 meters above sea level

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
March				
13	10.9	7.2	13.9	4.4
14	11.7	6.1	16.0	6.6
15	13.7	12.9	15.4	17.8
16	14.3	10.8	22.4	15.2
17	13.6	9.9	15.6	28.7
18	16.5	10.5	22.8	12.0
19	17.4	13.9	23.0	36.2
20	20.7	15.5	25.5	12.0
28	22.7	9.4	25.4	15.0
29	18.3	15.1	29.0	45.4
30	13.3	12.1	20.4	30.4
31	13.7	9.9	17.9	30.0
April				
1	13.9	11.4	21.8	5.6
2	13.9	11.5	16.2	52.4
3	--	9.5	14.4	--
10	23.9	24.7	27.9	25.3
11	23.0	15.6	28.3	10.7
12	--	26.1	32.3	--
26	--	16.4	17.5	18.0
27	23.5	16.1	26.0	34.6
28	23.7	22.5	27.8	41.4
29	15.1	15.5	21.9	36.0
30	17.9	15.5	18.0	32.4
May				
1	19.0	16.7	22.8	40.2
2	22.9	20.0	23.9	45.2
3	24.5	23.3	26.3	36.0
4	28.1	23.3	29.0	22.6
5	20.3	18.9	29.7	21.6
6	20.3	18.6	21.8	10.8
7	20.4	17.8	23.0	15.8
8	24.4	18.4	29.6	8.0
9	16.4	13.4	30.6	18.4
10	15.5	13.5	17.8	20.8
11	18.6	15.1	23.3	11.0
12	29.5	17.1	36.1	13.1
13	29.9	27.1	36.3	18.6
14	22.4	19.8	27.3	26.2

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
May (Continued)				
15	28.6	24.8	30.4	33.7
16	25.1	20.6	33.9	25.7
17	20.9	18.5	22.9	25.4
18	27.5	20.1	34.5	11.4
19	19.0	17.3	20.8	35.7
20	22.8	16.3	25.5	10.0
21	34.1	22.2	39.4	10.5
22	25.9	21.8	32.9	30.8
23	17.6	13.8	22.8	18.6
24	22.0	14.4	26.6	45.4
25	23.7	22.1	25.8	45.0
26	28.4	21.5	32.1	38.0
27	25.4	19.0	33.4	51.8
28	14.2	13.6	20.0	59.7
29	11.5	9.4	14.3	46.5
30	10.8	9.6	13.3	42.4
31	13.6	9.0	16.6	37.3
June				
1	28.6	25.3	30.8	52.5
2	24.0	27.9	34.0	31.8
3	17.1	16.4	22.8	47.2
4	19.4	16.2	24.1	19.2
5	24.3	16.1	23.9	17.2
6	26.5	23.9	28.2	22.8
7	35.1	25.4	35.9	43.5
8	32.5	30.0	35.8	37.3
9	32.1	28.6	35.5	17.5
10	31.5	28.6	34.4	23.4
11	33.9	31.4	34.4	23.2
12	36.6	31.6	38.5	21.4
13	44.4	36.6	46.8	8.4
14	44.3	40.5	48.8	13.5
15	34.5	31.9	40.2	26.4
16	28.0	26.8	32.8	31.5
17	25.4	23.6	28.4	33.4
18	24.6	22.2	26.8	19.7
19	25.1	22.1	27.5	20.5
30	17.5	15.8	26.1	25.5
21	19.3	14.4	22.8	12.6
22	17.9	15.1	25.6	22.3
23	14.3	12.6	16.8	35.1
24	16.1	13.7	17.8	32.8
25	16.0	13.5	18.3	28.0
26	23.9	17.3	28.2	27.5

Date	Temperature, -°C		Mean Wind Speed mph
	Mean	Minimum	
June (continued)			
27	32.0	26.9	25.8
28	34.6	28.9	12.6
29	40.4	32.8	14.5
30	34.8	32.0	24.8
July			
1	27.2	22.5	31.7
2	24.2	22.1	29.5
3	23.3	20.0	25.7
4	26.9	20.6	21.6
5	27.8	25.8	8.1
6	34.7	28.6	28.2
7	23.4	17.2	31.0
8	18.9	15.5	36.7
9	19.5	17.6	46.2
10	20.7	19.2	29.0
11	21.9	18.0	12.1
12	22.3	19.6	8.4
13	23.5	20.3	9.4
14	26.8	22.4	20.1
15	23.3	21.8	62.1
16	20.4	19.4	44.3
17	27.9	22.8	11.5
18	27.9	22.8	9.4
19	29.5	20.5	27.0
20	27.2	23.3	18.2
21	27.0	24.8	26.1
22	32.6	24.0	12.3
23	37.6	34.2	9.3
24	29.1	22.7	21.8
25	22.1	18.1	24.8
26	20.9	17.0	25.5
27	29.2	21.7	34.0
28	29.1	25.2	37.0
29	25.1	20.7	28.5
30	22.3	18.9	40.7
31	23.6	21.1	35.1
August			
1	27.3	22.9	33.4
2	17.7	15.3	38.3
3	22.0	16.6	35.1
4	29.3	22.9	21.9
5	22.7	21.1	45.4
6	23.3	19.8	37.7

Date	Temperature, -°C		Mean Wind Speed mph
	Mean	Minimum	

August
(continued)

7	25.1	21.8	28.3	33.4
8	28.6	21.8	31.3	25.7
9	29.6	27.8	33.9	28.7
10	23.4	18.1	28.4	18.6
11	25.4	21.8	31.4	24.0
12	21.8	20.5	23.9	35.7
13	21.5	20.0	24.9	35.7
14	20.5	18.3	24.1	52.3
15	19.0	17.6	25.0	55.2
16	20.5	17.6	23.6	47.6
17	26.0	20.9	30.1	22.3
18	31.7	28.6	32.9	15.0
19	27.2	23.6	34.0	8.4
20	26.7	25.5	32.2	46.0
21	24.0	22.3	27.2	42.8
22	24.0	21.8	25.8	36.0
23	24.5	23.0	27.1	53.6
24	17.8	14.9	26.9	24.4
25	15.6	13.8	21.5	51.8
26	12.3	9.4	16.3	29.1
27	12.7	11.1	15.0	50.5
28	14.2	12.2	15.0	29.1
29	19.8	14.2	22.4	11.2
30	23.5	18.8	27.8	14.6
31	26.9	22.5	30.1	16.3

September

1	24.1	21.7	33.0	33.1
2	20.2	16.3	23.2	25.2
3	18.2	15.1	27.2	31.2
4	16.8	12.5	17.0	18.4
5	27.2	20.8	32.5	10.4
6	23.9	15.9	30.5	10.2
7	26.7	18.6	32.5	10.0
8	26.5	19.8	33.0	11.0
9	20.3	17.9	32.2	62.1
10	14.6	13.9	27.2	56.0
11	15.6	10.0	20.5	34.7
12	17.3	13.8	18.9	26.1
13	21.1	13.4	27.1	7.5
14	26.3	19.8	30.0	8.4
15	22.4	12.8	33.4	27.0
16	20.8	16.7	25.5	58.3
17	22.5	20.1	25.5	57.0
18	24.1	20.5	25.7	38.7

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
September (continued)				
19	29.8	24.1	32.2	21.7
20	30.6	27.9	35.1	27.4
21	23.2	20.3	31.4	18.5
22	20.8	18.6	25.0	23.3
23	20.4	18.0	21.6	31.0
24	21.6	19.4	23.6	30.2
25	21.4	19.5	23.6	38.7
26	20.8	18.9	23.2	33.8
27	19.4	16.8	21.4	57.0
28	17.1	15.8	21.1	54.8
29	16.1	13.2	18.6	46.8
30	18.5	13.8	14.4	64.0
October				
1	17.3	14.6	20.7	11.1
2	14.5	6.7	26.1	12.4
3	17.4	17.2	28.9	4.6
4	29.0	11.4	39.1	8.3
5	28.3	--	38.9	14.1
6	16.8	--	33.9	18.7
7	17.4	--	20.5	22.2
8	16.4	--	18.9	44.8
9	14.5	--	16.9	44.8
10	12.9	--	15.0	48.5
11	13.5	--	14.8	51.4
12	15.5	--	21.4	53.1
13	17.7	--	18.9	45.4
14	22.1	--	26.0	26.4
15	22.4	12.8	27.5	10.1
16	20.9	14.9	30.7	13.4
17	18.9	13.3	20.8	18.2
18	21.3	7.2	27.6	4.8
19	21.8	15.1	34.0	22.3
20	18.8	14.7	24.8	24.5
21	19.1	12.8	23.6	26.2
22	23.0	21.6	25.0	46.3
23	26.0	22.3	30.6	26.0
24	22.0	14.8	30.1	38.5
25	18.6	12.6	22.6	34.5
26	18.6	18.9	19.3	9.0
27	20.8	21.8	22.9	10.0
28	23.9	19.4	28.8	25.3
29	17.3	13.3	24.5	32.8
30	13.5	--	15.1	18.4
31	14.9	--	20.0	12.0

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
November				
1	17.5	14.3	19.0	37.0
2	18.6	16.8	20.1	41.6
3	16.7	14.1	20.8	42.8
4	13.7	9.3	16.7	20.3
5	11.8	7.4	18.6	16.3
6	10.8	2.2	13.0	9.7
7	17.5	11.1	22.4	20.1
8	15.4	12.2	21.1	26.1
9	14.0	12.0	15.5	34.7
10	13.3	8.5	15.0	41.1
11	16.5	13.7	17.8	36.0
12	17.5	13.3	19.4	32.1
13	16.7	13.9	22.9	33.0
14	14.5	12.8	16.6	33.0
15	13.8	10.7	15.0	32.1
16	13.1	12.8	15.6	21.0
17	12.8	3.0	16.8	9.6
18	12.5	3.6	16.5	10.8
19	9.8	4.9	18.6	20.5
20	7.7	0.6	11.6	9.2
21	9.5	2.3	18.1	3.8
22	16.3	6.7	16.3	19.5
23	18.4	16.6	21.0	36.3
24	15.1	12.5	18.9	32.4
25	14.1	9.4	16.5	17.6
26	16.5	13.9	21.5	25.0
27	13.6	11.4	17.3	29.7
28	11.4	7.2	16.1	10.7
29	13.6	5.6	20.5	8.2
30	17.3	6.7	22.6	6.5
December				
1	17.8	9.6	25.1	17.7
2	14.1	11.6	18.8	28.8
3	8.9	5.5	14.1	30.5
4	9.1	6.2	10.5	14.7
5	14.5	--	17.4	13.8
6	15.6	--	20.8	16.0
7	12.1	--	17.8	15.7
8	12.7	--	16.1	17.5
9	11.0	--	19.1	17.7
10	8.9	--	10.8	20.1
11	9.5	--	14.6	18.8
12	8.4	--	15.8	8.6
13	7.3	--	10.1	10.0

Date	Temperature, -°C			Mean Wind Speed mph
	Mean	Maximum	Minimum	
December (continued)				
14	6.9	--	13.3	17.1
15	6.6	--	8.6	13.8
16	7.2	--	9.6	19.7
17	8.0	--	11.1	49.3
18	7.0	--	8.1	67.3
19	7.1	--	8.6	38.3
20	7.3	--	11.2	16.7
21	7.0	--	12.5	15.7
22	9.2	--	14.4	20.6
23	10.4	--	15.3	18.0
24	9.8	--	18.0	11.8
25	9.1	--	11.9	16.7
26	8.7	--	11.6	14.3
27	3.9	--	15.5	5.0
28	6.9	--	11.5	28.0
29	9.6	--	12.0	45.4
30	8.0	--	10.8	28.7
31	7.7	--	10.8	29.6
January				
1	8.2	--	10.3	19.3
2	9.5	--	11.1	20.1
3	10.3	8.8	13.8	39.5
4	8.6	6.6	10.7	39.0
5	9.3	7.1	12.9	44.2
6	6.4	4.3	7.9	23.5
7	4.0	1.2	6.5	7.0
8	8.1	0.5	16.0	7.5
9	6.8	+2.2	15.1	9.0
10	7.6	0.4	15.5	6.0
11	12.7	6.1	18.4	18.5
12	9.0	0.1	17.8	10.3
13	11.2	7.5	16.0	10.0
14	10.5	6.6	12.2	18.0
15	8.7	5.0	13.8	12.2
16	10.1	--	11.1	35.0

Wind Direction and Mean Temperature (°C) at Wilkes Base, March 1957-January 1958

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	C
Mar	3.3	4.7	4.7	2.1	3.1	6.0	5.1	4.1	6.4	1.4	8.3	3.9	6.9	5.1	3.0	3.3	3.1
Apr	7.6	4.2	3.4	4.1	3.6	4.1	8.4	9.8	8.6	7.3	6.6	8.3	--	3.9	6.4	8.3	8.1
May	10.1	12.9	9.4	5.8	8.9	9.1	11.5	14.0	15.6	12.8	12.6	5.0	--	15.8	13.0	10.0	13.5
Jun	8.0	17.6	19.0	20.4	13.6	19.0	16.5	16.0	19.0	16.6	6.8	15.5	10.5	--	--	12.2	20.1
Jul	14.5	17.1	17.8	15.3	16.5	11.7	16.1	19.0	19.0	19.6	20.0	16.1	--	13.9	--	13.3	18.8
Aug	9.1	14.9	12.4	7.8	10.6	9.4	10.3	14.1	15.9	11.1	11.3	--	5.0	8.0	5.8	4.1	16.1
Sep	17.8	15.8	12.4	12.3	9.4	8.5	12.3	12.3	10.9	11.0	10.5	10.0	5.0	--	5.3	11.9	12.5
Oct	9.4	10.6	10.0	11.9	11.3	7.3	10.8	9.5	9.5	9.8	5.5	3.9	5.1	8.2	7.2	4.9	10.5
Nov	2.2	3.6	4.1	5.2	6.9	5.4	5.6	4.9	4.6	3.6	2.1	2.7	3.6	2.0	2.3	2.9	4.2
Dec	+0.5	0.1	0.7	1.9	1.1	0.3	1.1	+0.1	+0.2	+0.5	+0.5	+2.1	+1.3	+1.8	+1.4	+1.3	+1.0
Jan	17.8	0.5	0.7	0.0	+0.3	+0.6	0.6	0.1	00	+0.8	+1.5	+2.4	0.4	+1.1	+1.0	+1.0	+0.5
Mean	7.4	9.3	8.6	7.9	7.7	7.3	8.9	9.5	9.9	8.4	7.4	6.1	4.4	6.0	4.5	6.3	9.6

Wind Direction and Mean Temperature (°C) at S-2, March 1957-January 1958

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	C
Mar	12.6	--	15.0	12.0	16.3	17.3	16.1	--	--	--	--	--	--	--	13.6	10.5	10.9
Apr	--	--	14.4	15.0	18.2	20.1	19.6	--	--	--	--	--	--	--	--	--	--
May	25.0	29.4	18.4	16.5	19.5	21.8	25.5	29.1	23.3	--	--	--	19.4	--	24.4	27.8	--
Jun	31.6	--	32.8	33.4	22.1	27.5	29.6	--	--	--	--	--	--	--	--	--	36.9
Jul	22.8	--	20.9	27.0	24.0	25.2	29.5	30.0	28.2	25.5	25.5	28.9	26.3	23.9	23.3	29.7	24.4
Aug	--	--	14.1	19.5	22.9	22.9	25.1	--	--	--	--	--	24.8	--	--	--	--
Sep	30.0	--	23.0	29.1	20.0	20.5	22.5	28.3	28.3	26.6	--	--	22.8	17.5	25.9	30.5	25.6
Oct	--	--	15.1	23.8	21.5	16.9	21.4	20.2	20.2	19.4	18.0	15.5	15.3	16.9	17.2	--	--
Nov	8.9	--	12.4	11.9	13.1	15.3	15.9	11.1	11.1	10.3	10.0	--	--	5.5	4.4	--	--
Dec	--	--	4.6	8.3	9.3	9.8	10.4	--	--	6.1	7.3	--	--	--	8.3	4.4	9.4
Jan	--	--	7.7	9.8	9.0	11.1	15.5	--	6.1	12.5	1.9	--	2.1	--	1.1	--	--
Mean	22.7	29.4	16.2	18.8	17.8	18.9	20.9	23.7	19.9	16.8	12.5	22.2	18.4	16.0	14.8	20.6	21.4

Number of Observations and the Percentage Frequency of the Different Wind Direction at Base

Wind Direc- tion	March		April		May		June		July		Aug		Sep		Oct		Nov		Dec		Jan	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
N	8	3.6	14	5.8	4	1.6	2	0.3	9	3.6	4	1.6	1	0.4	3	1.2	4	1.7	9	3.6	14	5.6
NNE	16	7.2	7	2.8	19	7.7	7	3.0	14	5.7	5	2.0	17	7.1	21	8.5	11	4.6	21	8.5	22	8.8
NE	21	9.4	23	9.6	24	9.7	18	7.5	33	13.3	34	13.7	20	8.3	32	12.9	32	13.3	28	11.3	38	15.3
ENE	22	9.8	22	9.2	13	5.2	13	5.4	13	5.2	13	5.3	15	6.3	13	5.2	6	2.5	23	9.3	9	3.6
E	30	13.4	41	17.1	23	9.3	30	12.5	11	4.4	32	12.9	43	17.9	16	6.4	28	11.7	17	6.8	15	6.0
ESE	11	4.9	18	7.5	22	8.9	18	7.5	20	8.1	32	12.9	41	17.1	43	17.3	23	9.6	8	3.2	15	6.0
SE	10	4.5	13	5.4	11	4.4	14	6.8	6	2.4	7	2.8	10	4.2	8	3.2	16	6.7	8	3.2	11	4.4
SSE	16	7.2	16	6.7	27	10.9	12	5.0	14	5.6	10	4.0	16	6.7	11	4.4	14	5.0	17	6.8	11	4.4
S	33	14.7	47	19.6	34	13.7	41	12.1	50	20.2	41	16.5	25	10.4	20	8.1	19	7.9	20	8.1	17	6.8
SSW	6	2.7	16	6.7	16	6.5	15	6.3	20	8.1	12	4.9	18	7.5	13	5.2	11	4.6	7	2.8	15	6.0
SW	2	0.9	5	2.1	9	3.6	5	2.1	3	1.2	8	3.2	2	0.8	4	1.6	5	2.1	12	4.8	11	4.4
WSW	3	1.3	1	0.4	2	0.8	1	0.4	1	0.4	0	0.0	1	0.4	1	0.4	14	5.8	6	2.4	4	1.6
W	2	0.9	0	0.0	0	0.0	1	0.4	0	0.0	1	0.4	1	0.4	6	2.4	2	0.8	3	1.2	2	0.8
WNW	1	0.4	1	0.4	2	0.8	0	0.0	1	0.4	2	0.8	0	0.0	5	2.0	6	2.5	3	1.2	6	2.4
NW	5	2.2	1	0.4	2	0.8	0	0.0	0	0.0	2	0.8	2	0.8	9	3.6	5	2.1	9	3.6	8	3.2
NNW	11	4.9	4	1.7	1	0.4	2	0.8	18	7.3	3	1.2	4	1.7	7	2.8	7	2.9	9	3.6	12	4.8
Calm	27	12.0	11	4.6	39	15.7	61	25.4	35	14.1	42	17.0	24	10.0	36	14.5	37	15.4	48	19.3	38	15.3
Total	224	100	240	100	248	100	240	100	248	100	248	100	240	100	248	100	240	100	248	100	248	100

Number of Observations and the Percentage Frequency of the Different Wind Directions at S-2

Wind Direc- tion	March		April		May		June		July		Aug		Sep		Oct		Nov		Dec		Jan	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
N	3	5.0	--	--	1	0.5	1	0.5	1	0.5	--	--	2	1.0	2	1.0	2	1.0	--	--	--	--
NNE	--	--	--	--	1	0.5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
NE	5	8.2	1	2.3	14	6.9	2	1.1	8	3.9	8	4.1	8	4.1	9	4.5	4	2.0	2	0.9	9	9.6
ENE	3	5.0	1	2.3	7	3.5	3	1.8	3	1.5	13	6.7	18	9.2	5	2.5	10	5.1	16	7.8	10	10.7
E	23	37.1	13	30.2	54	26.7	21	11.8	25	12.2	15	7.6	42	21.5	17	8.5	31	15.9	78	38.2	34	36.5
ESE	11	18.0	21	48.8	54	26.7	43	52.2	117	57.3	139	71.3	96	49.2	71	35.5	101	52.0	79	38.7	25	26.8
SE	9	14.7	7	16.3	62	30.7	56	31.5	22	10.7	15	7.6	13	6.7	68	34.0	26	13.4	18	8.8	1	1.0
SSE	--	--	--	--	2	1.0	--	--	6	2.9	--	--	1	0.5	8	4.0	5	2.5	--	--	--	--
S	--	--	--	--	1	0.5	--	--	9	4.4	2	1.0	--	--	4	2.0	10	5.1	--	--	2	2.1
SSW	--	--	--	--	--	--	--	--	1	0.5	--	--	1	0.5	1	0.5	2	1.0	1	0.4	2	2.1
SW	--	--	--	--	--	--	--	--	1	0.5	--	--	--	--	7	3.5	1	0.5	7	3.4	4	4.3
WSW	--	--	--	--	--	--	--	--	1	0.5	--	--	--	--	1	0.5	--	--	--	--	--	--
W	--	--	--	--	2	1.0	--	--	5	2.4	3	1.5	3	1.5	2	1.0	--	--	--	--	4	4.3
WNW	--	--	--	--	--	--	--	--	1	0.5	--	--	2	1.0	--	--	1	0.5	--	--	--	--
NW	2	3.3	--	--	1	0.5	--	--	1	0.5	--	--	4	2.0	5	2.5	1	0.5	1	0.4	2	2.1
NNW	2	3.3	--	--	3	1.5	--	--	1	0.5	--	--	1	0.5	--	--	--	--	1	0.4	--	--
Calm	3	5.0	--	--	--	--	2	1.1	2	0.9	--	--	4	2.0	--	--	--	--	1	0.4	--	--
Total	61	100	43	100	202	100	178	100	204	100	195	100	195	100	200	100	194	100	204	100	93	100

APPENDIX II
SNOW ACCUMULATION DATA

Accumulation Along S-2 Trail
18 October 1957 - 17 October 1959
(Cumulative water equivalent, cm)

Stake	1	2	3	4	5	6	7	8
Elevation (m)	1091	1016	944	861	772	673	574	467
1957								
18 Oct	*	*	*	*	*	*	*	--
15 Nov	--	--	--	--	--	--	--	*
1958								
2 Jan	-4.4	-3.1	-3.1	-2.8	-2.8	-1.3	0.2	0.6
22 Jan	-4.4	-4.0	-4.3	-3.3	-3.1	-1.7	-0.7	0.0
10 Feb	-3.1	-4.3	-4.6	-4.0	-4.4	-3.1	--	--
18 Mar	-4.0	-4.4	-0.5	-4.1	-4.9	-2.0	--	--
3 Apr	-2.4	--	--	-4.0	-4.6	-4.3	--	--
7 Apr	1.8	-4.6	0.2	-3.9	-4.6	-2.4	-2.2	--
17 Apr	-2.6	-3.9	0.2	-3.5	--	--	--	--
2 May	--	--	--	--	--	-3.9	-2.4	--
7 May	-3.3	-0.2	2.0	-0.4	3.0	-2.4	-2.0	0.0
5 Jun	3.0	0.7	2.4	-3.9	0.5	-1.7	--	1.3
14 Jul	--	--	--	-1.1	6.1	4.6	-0.5	5.0
22 Jul	--	--	--	--	--	6.1	9.1	8.0
1 Aug	--	--	--	--	--	--	--	9.8
4 Aug	8.3	5.0	9.1	9.4	11.1	4.6	7.6	--
3 Sep	8.1	8.0	12.7	9.1	10.7	7.7	10.0	10.6
12 Sep	--	--	--	--	--	--	--	10.9
16 Nov	7.7	11.6	12.4	11.1	14.4	7.7	10.7	14.0
7 Jan	7.7	8.9	10.9	10.4	10.9	8.7	7.4	12.2
17 Jan	7.4	8.7	10.5	10.2	10.5	8.3	9.4	13.0
30 Jan	--	8.9	10.2	10.0	10.5	7.9	10.2	12.8
29 Apr	--	--	--	--	--	12.1	13.9	--
17 Oct	12.2	16.2	15.5	16.9	13.1	18.0	16.5	17.9

* Stake set in.

Annual Accumulation Along S-2 Trail
(cm Water)

Time Interval						Average Annual Accumulation
	One Year	One Year	One Year	One Year	Two Years	
	15 Nov 1957	2 Jan 1958	22 Jan 1958	7 Apr 1958	18 Oct 1957	18 Oct 1957
Stake	16 Nov 1958	7 Jan 1959	17 Jan 1959	29 Apr 1959	17 Oct 1959	17 Oct 1959
1	--	12.2	11.8	--	12.2	6.1
2	--	12.0	12.4	--	16.2	8.1
3	--	14.1	14.8	--	15.5	7.8
4	--	13.1	13.5	--	16.9	8.5
5	--	13.7	13.7	--	13.1	6.6
6	--	9.6	13.6	14.5	18.0	9.0
7	--	8.0	10.2	16.1	16.5	8.3
8	14.1	11.6	12.9	--	17.9*	9.0

*For the period 15 Nov 1957 to 17 October 1959.

Accumulation at S-2
Stake Net
20 March 1957--10-17 January 1959
(Cumulative water equivalent, cm)

	Stake												
Date	A	B	C	D	E	F	G	H	I	J	K	L	Mean
1957													
20 Mar		*	*	*	*	*	*	*	*	*	*	*	
18 Jun	*	4.3	3.9	7.2	4.4	3.7	2.2	4.8	9.6	5.4	7.6	6.1	5.4
15 Oct	9.3	11.1	6.3	7.0	4.4	7.8	1.8	7.4	11.1	5.5	7.0	5.5	7.0
9 Dec	7.0	9.1	6.1	5.2	4.3	4.4	1.1	5.5	12.4	--	0.4	4.6	5.5
1958													
18 Jan	10.5	7.4	7.4	3.1	7.2	8.7	0.0	4.1	8.9	3.9	5.4	6.3	6.1
20 May-1 Jun	--	19.6	15.5	2.0	15.9	12.2	4.1	19.2	16.3	10.0	10.7	14.1	12.7
1959													
10-17 Jan	--	24.8	29.6	10.7	25.9	24.4	14.4	29.6	28.9	19.6	24.4	27.7	23.6

* Stake set in.

Accumulation at S-2
Weather Bureau Stakes
11 April 1957 - 16 October 1959
(Cumulative water equivalent, cm)
(Average of the three stakes)

1957		cm	1957		cm	1958		cm	1958		cm
		water			water			water			water
13	Mar	--	7	Aug	5.1	26	Mar	14.2	7	May	19.8
14		0.9	10		5.1	27		14.2	15		20.6
15		1.9	17		5.3	28		14.2	17		14.2
16		1.9	22		5.1	29.		14.2	19		20.6
28		1.9	28		7.9	30		14.2	4	Aug	27.7
29*		2.7	4	Sep	7.9	31		14.2	3	Sep	31.2
11	Apr	0.5	6		9.1	1	Apr	13.2	4		31.0
27		2.2	12		8.6	3		14.5	16	Nov	31.2
7	May	2.2	14		8.6	4		13.2		1959	
10		6.6	25		8.1	5		13.2	8	Jan	30.7
14		6.6	1	Oct	13.7	6		13.2	30		30.0
18		4.6	14		12.2	7		14.2	16	Oct	40.4
21		5.3	21		11.4	8		14.2			
31		4.1	26		11.2	10		15.0			
19	Jun	3.0	31		10.9	11		14.2			
26		3.8	11	Nov	10.4	12		14.2			
4	Jul	5.1	18		10.4	13		14.2			
11		5.1		1958		14		14.2			
17		5.3	2	Jan	8.4	15		14.2			
31		5.6	6		9.1	16		14.2			

*On 29 March the stakes were moved a greater distance from the S-2 ~~Jamesway~~ hut to avoid drifting.

Annual Accumulation at S-2
Weather Bureau Stakes
(cm water)

<u>1957 Cumulative Accumulation</u>		<u>1958 Cumulative Accumulation</u>		<u>1951 Cumulative Accumulation</u>		<u>Annual Accumulation One Year Two Years</u>	
		2 Jan	8.4	8 Jan	30.7	22.3	
11 Apr	0.5	1 Apr	13.2			12.7	
7 May	2.2	7 May	19.8			17.6	
7 Aug	5.1	4 Aug	27.7			22.6	
4 Sep	7.9	3 Sep	31.2			23.3	
1 Oct	13.7			16 Oct	40.4		26.7
11 Nov	10.4	16 Nov	31.2			20.8	

Annual Accumulation at S-2 Deep Pit

Summer*	Depth h (cm)	Δh (cm)	Annual Accumulation gm cm ⁻²	Cumulative Accumulation gm cm ⁻²	Running Mean gm cm ⁻²	5-year Mean Accumulation gm cm ⁻²
1957	18	40	17.6	17.6	17.6	
1956	58	27	12.1	29.7	14.8	
1955	85	28	13.6	43.3	14.4	13.0
1954	113	30	12.3	55.6	13.9	
1953	143	23	9.5	65.1	13.0	
1952	166	30	14.1	79.2	13.2	
1951	196	32	15.0	94.2	13.4	
1950	228	34	15.8	110.0	13.7	13.3
1949	262	15	7.8	117.8	13.1	
1948	277	30	13.6	131.4	13.1	
1947	307	26	11.5	142.9	13.0	
1946	333	27	12.8	155.7	13.0	
1945	360	25	11.6	167.3	12.9	12.5
1944	385	35	15.9	183.2	13.1	
1943	420	21	10.5	193.7	12.9	
1942	441	36	18.7	212.4	13.3	
1941	477	23	12.4	224.8	13.2	
1940	500	35	18.0	242.8	13.5	13.6
1939	535	15	8.2	251.0	13.2	

*Summers are given as the date of the new year to avoid giving two years to denote the summer. Therefore, a summer period 1954-1955 is given as 1955.

Summer*	Depth h (cm)	Δh (cm)	Annual Accumulation gm cm ⁻²	Cumulative Accumulation gm cm ⁻²	Running Mean gm cm ⁻²	5-year Mean Accumulation gm cm ⁻²
1938	550					
		20	10.6	261.6	13.1	
1937	570					
		29	16.1	277.7	13.2	
1936	589					
		15	8.5	286.2	13.0	
1935	604					
		16	8.9	295.1	12.8	11.3
1934	620					
		15	8.4	303.5	12.6	
1933	635					
		26	14.7	318.2	12.7	
1932	661					
		14	7.8	326.0	12.5	
1931	675					
		14	8.0	334.0	12.3	
1930	689					
		35	20.0	354.0	12.6	11.2
1929	724					
		20	11.7	365.7	12.6	
1928	744					
		14	8.4	374.1	12.5	
1927	758					
		21	12.7	386.8	12.5	
1926	779					
		20	11.9	398.7	12.5	
1925	799					
		20	12.0	410.7	12.4	12.0
1924	819					
		24	14.2	424.9	12.5	
1923	843					
		16	9.4	434.3	10.9	
1922	859					
		20	11.5	445.8	10.9	
1921	879					
		23	13.6	459.4	10.9	
1920	902					
		26	15.8	475.2	11.0	13.2
1919	928					
		18	11.3	486.5	11.0	
1918	946					
		22	13.7	500.2	11.1	
1917	968					
		22	13.5	513.7	11.1	
1916	990					
		20	12.5	526.2	11.2	

Summer*	Depth h (cm)	Δh (cm)	Annual Accumulation gm cm ⁻²	Cumulative Accumulation gm cm ⁻²	Running Mean gm cm ⁻²	5-year Mean Accumulation gm cm ⁻²
1915	1010					
		44	27.5	553.7	11.5	16.8
1914	1054					
		22	13.7	567.4	11.6	
1913	1076					
		27	16.9	584.3	11.7	
1912	1103					
		39	24.8	609.1	11.9	
1911	1142					
		16	10.1	619.2	11.9	
1910	1158					
		27	17.3	636.5	12.0	15.2
1909	1185					
		20	13.0	649.5	12.0	
1908	1205					
		17	11.1	660.6	12.1	
1907	1222					
		18	11.7	672.3	12.0	
1906	1240					
		23	15.0	687.3	12.0	
1905	1263					
		19	12.4	699.7	12.0	14.4
1904	1282					
		29	19.0	718.7	12.2	
1903	1311					
		21	13.8	732.5	12.2	
1902	1332					
		17	11.2	743.7	12.2	
1901	1349					
		20	13.2	756.9	12.2	
1900	1369					
		17	11.3	768.2	12.2	13.2
1899	1386					
		20	13.2	781.4	12.2	
1898	1406					
		25	16.9	798.3	12.3	
1897	1431					
		13	8.8	807.1	12.2	
1896	1444					
		15	10.2	817.3	12.2	
1895	1459					
		16	10.9	828.2	12.2	11.3
1894	1475					
		19	12.9	841.1	12.2	
1893	1494					
		20	13.7	854.8	12.2	

Summer*	Depth h (cm)	Δh (cm)	Annual Accumulation gm cm ⁻²	Cumulative Accumulation gm cm ⁻²	Running Mean gm cm ⁻²	5-year Mean Accumulation gm cm ⁻²
1892	1514					
		13	8.9	863.7	12.2	
1891	1527					
		23	15.9	879.6	12.2	
1890	1550					
		20	13.6	893.2	12.2	13.7
1889	1570					
		25	17.0	910.2	12.3	
1888	1595					
		19	13.0	923.2	12.3	
1887	1614					
		32	21.8	945.0	12.4	
1886	1646					
		24	16.4	960.4	12.5	
1885	1670					
		15	10.3	970.7	12.5	13.6
1884	1685					
		16	11.0	981.7	12.4	
1883	1701					
		14	9.6	991.3	12.4	
1882	1714					
		31	21.0	1012.3	12.5	
1881	1746					
		18	12.6	1024.9	12.5	
1880	1764					
		27	19.2	1044.1	12.6	16.4
1879	1792					
		20	14.2	1058.3	12.6	
1878	1811					
		21	14.9	1073.2	12.6	
1877	1832					
		20	14.4	1087.6	12.6	
1876	1852					
		20	14.3	1101.9	12.7	
1875	1872					
		16	11.3	1113.2	12.7	14.4
1874	1888					
		13	9.4	1122.6	12.7	
1873	1901					
		31	22.6	1145.2	12.7	
1872	1932					
		15	10.7	1155.9	12.7	
1871	1947					
		15	10.6	1166.5	12.7	
1870	1962					
		49	35.0	1201.5	12.7	15.3

Summer*	Depth h (cm)	Δh (cm)	Annual Accumulation gm cm ⁻²	Cumulative Accumulation gm cm ⁻²	Running Mean gm cm ⁻²	5-year Mean Accumulation gm cm ⁻²
1869	2011					
		13	9.2	1210.7	13.6	
1868	2024	15	10.8	1221.5	13.6	
1867	2039	17	12.2	1233.7	13.7	
1866	2054	20	14.4	1248.1	13.6	
1865	2074	15	10.8	1258.9	13.5	13.6
1864	2091	20	14.5	1273.4	13.5	
1863	2111	22	16.2	1289.6	13.6	
1862	2132	21	15.3	1304.9	13.6	
1861	2153	15	11.0	1315.9	13.6	
1860	2168	25	18.2	1334.1	13.6	17.1
1859	2193	41	30.0	1364.1	13.8	
1858	2234	15	11.0	1375.1	13.7	
1857	2249	13	9.7	1384.8	13.7	
1856	2262	15	11.2	1396.0	13.7	
1855	2277	11	8.1	1404.1	13.6	10.5
1854	2288	13	9.9	1414.0	13.6	
1853	2301	18	13.7	1427.7	13.6	
1852	2319	18	13.6	1441.3	13.6	
1851	2337	34	25.0	1466.3	13.7	
1850	2371	19	14.0	1480.3	13.7	17.4
1849	2390	32	23.5	1503.8	13.8	
1848	2422	15	11.1	1514.9	13.8	
1847	2437	13	9.6	1524.5	13.7	

Summer*	Depth h (cm)	Δh (cm)	Annual Accumulation gm cm ⁻²	Cumulative Accumulation gm cm ⁻²	Running Mean gm cm ⁻²	5-year Mean Accumulation gm cm ⁻²
1846	2450					
		14	10.4	1534.9	13.7	
1845	2464					
		17	12.7	1547.6	13.7	12.5
1844	2481					
		21	15.4	1563.0	13.7	
1843	2502					
		19	14.2	1577.2	13.7	
1842	2521					
		15	11.2	1588.4	13.7	
1841	2536					
		8	6.0	1594.4	13.6	
1840	2544					
		17	12.6	1607.0	13.6	10.1
1839	2561					
		10	7.4	1614.4	13.6	
1838	2571					
		18	13.3	1627.7	13.6	
1837	2589					
		15	11.1	1638.8	13.5	
1836	2604					
		18	13.4	1652.2	13.5	
1835	2622					
		17	12.6	1664.8	13.5	14.3
1834	2639					
		19	14.4	1679.2	13.5	
1833	2658					
		26	19.8	1699.0	13.6	
1832	2684					
		39	30.0	1729.0	13.7	
1831	2723					
		17	13.4	1742.4	13.7	
1830	2741					
		12	9.5	1751.9	13.7	17.1
1829	2753					
		23	18.4	1770.3	13.7	
1828	2776					
		18	14.1	1784.4	13.7	
1827	2794					
		19	14.6	1799.0	13.7	
1826	2813					
		21	16.3	1815.3	13.7	
1825	2834					
		21	16.7	1832.0	13.8	12.5
1824	2855					
		11	8.8	1840.8	13.7	

Summer*	Depth h (cm)	Δh (cm)	Annual Accumulation gm cm ⁻²	Cumulative Accumulation gm cm ⁻²	Running Mean gm cm ⁻²	5-year Mean Accumulation gm cm ⁻²
1823	2866					
		8	6.4	1847.2	13.7	
1822	2874					
		21	16.0	1863.2	13.7	
1821	2895					
		13	9.6	1872.8	13.7	
1820	2908					
		25	18.6	1891.4	13.7	13.0
1819	2933					
		19	14.4	1905.8	13.7	
1818	2952					
		9	6.6	1912.4	13.7	
1817	2961					
		9	7.1	1919.5	13.6	
1816	2970					
		13	10.3	1929.8	13.6	
1815	2983					
		14	10.8	1940.6	13.6	11.8
1814	2997					
		23	17.2	1957.8	13.6	
1813	3020					
		17	13.4	1971.2	13.6	
1812	3037					
		15	11.7	1982.9	13.6	
1811	3052					
		11	8.5	1991.4	13.5	
1810	3063					
		12	9.3	2000.7	13.5	9.0
1809	3075					
		10	7.7	2008.4	13.5	
1808	3085					
		10	7.8	2016.2	13.4	
1807	3095					
		26	20.2	2036.4	13.5	
1806	3121					
		12	9.5	2045.9	13.5	
1805	3133					
		16	12.5	2058.4	13.5	12.2
1804	3149					
		16	12.6	2071.0	13.5	
1803	3165					
		8	6.0	2077.0	13.4	
1802	3173					
		9	6.8	2083.8	13.4	
1801	3182					
		31	24.0	2107.8	13.4	

Summer*	Depth h (cm)	Δh (cm)	Annual Accumulation gm cm ⁻²	Cumulative Accumulation gm cm ⁻²	Running Mean gm cm ⁻²	5-year Mean Accumulation gm cm ⁻²
1800	3213					
		12	9.2	2117.0	13.4	14.0
1799	3225					
		17	13.2	2130.2	13.4	
1798	3242					
		21	16.6	2146.8	13.4	
1797	3263					
		14	11.3	2158.1	13.4	
1796	3277					
		13	10.6	2168.7	13.4	
1795	3290					
		17	14.2	2182.9	13.4	12.3
1794	3307					
		14	11.5	2194.4	13.4	
1793	3321					
		17	13.8	2208.2	13.4	
1792	3338					
		16	12.8	2221.0	13.4	
1791	3354					
		14	11.4	2232.4	13.4	
1790	3368					
		18	14.7	2247.1	13.4	12.7
1789	3386					
		15	12.3	2259.4	13.4	
1788	3401					
		15	12.2	2271.6	13.4	
1787	3416					
		10	8.2	2279.8	13.3	
1786	3426					
		14	11.5	2291.3	13.3	
1785	3440					
		13	10.7	2302.0	13.3	
1784	3453					
		21	17.3	2319.3	13.3	
1783	3474					

APPENDIX III

ICE MOVEMENT DATA

Vanderford Glacier: Movement State Coordinates

Date	Stake	x(m)	y(m)	h(m)
3 March 1957	1	567.3	239.4	51.4
	4	534.0	1362.4	36.8
	5	791.1	1486.7	33.3
	6	818.1	1658.0	41.4
	7	999.9	1915.0	38.8
	8A	835.7	2193.4	42.5
	9	692.6	3308.6	60.0
	10A	1484.1	4071.6	56.5
1 October 1957	1	567.2	239.2	
	2	592.1	866.8	
	4	544.6	1354.7	
	5	836.7	1455.1	
	6	844.3	1620.1	
	7	1103.4	1863.3	
	8A	968.0	2137.0	
	9	1030.1	3201.7	
	10B	1935.1	3795.5	
23 October 1957	1	567.3	239.4	49.7
	2	592.1	867.1	38.5
	4	546.1	1355.6	33.7
	5	841.6	1452.5	29.3
	6	891.4	1616.6	39.1
	7	1116.1	1862.3	38.0
	8A	982.6	2134.3	40.6
	8B	1023.2	2554.6	45.0
	9	1066.8	3196.5	54.7
	10A	1925.1	3948.7	53.8
	10B	1977.8	3785.8	57.2
	11	2775.3	4651.8	79.6
10 January 1958	1	567.2	239.3	48.6
	4	550.2	1352.8	33.2
	5	858.0	1441.6	31.4
	6	916.1	1603.5	41.1
	7	1153.7	1843.1	39.6
	8A	1031.7	2114.4	42.6
	8B	1105.2	2525.8	44.7
	9	1192.9	3153.2	57.1
	10A	2074.6	3906.2	56.7
	10B	2127.2	3746.2	56.5
	11	2935.2	4614.3	77.5

Date	Stake	x(m)	y(m)	h(m)
6-7 March 1958	1	568.4	237.6	49.4
	4A	706.4	831.8	37.3
	5	869.0	1431.6	31.0
	6	931.1	1590.8	41.2
	7	1175.5	1818.4	40.1
	8A	1065.4	2096.9	42.8
	8B	1161.8	2498.4	44.7
	9	1279.5	3113.4	54.9
	10A	2167.4	3846.3	55.2
	11	3024.5	4547.3	76.0
30 November 1958	1	567.7	283.3	49.25
	4A	705.7	829.7	37.0
	5	924.5	1398.2	30.0
	6	1013.0	1550.1	41.7
	7	1312.1	1779.4	40.8
	8B	1444.7	2442.0	40.4
	9	1722.6	3010.3	55.5
	10A	2713.7	3760.4	55.1
	11	3615.3	4484.3	74.2

S-2 Stake Net Triangulation:
16-20 March 1957

Angles	Observed	Corrected	Angles	Observed	Corrected
DBA	67°39'19"	67°39'18"	FDE	83°35'29"	83°35'28"
DAB	58°23'14"	- - -	DEF	54°13'24"	- - -
ADB	53°57'28"	- - -	EFD	42°11' 8"	- - -
DBF	62°20'14"	- - -	EDL	98°15' 8"	93°15'7"
BDF	58°14'31"	- - -	DLE	41°48'56"	- - -
DFB	59°25'14"	59°25'15"	LED	44°55'57"	- - -
FBG	49°59'25"	- - -	HCI	90°33'20"	90°33'10"
BFG	62° 0'26"	62° 0'25"	CIH	43°29'20"	- - -
FGB	68° 0'10"	- - -	IHC	45°57'20"	45°57'30"
DAL	47° 6'55"	47° 6'51"	JCI	89°32'16"	89°32' 0"
ADL	70°57'26"	- - -	CIJ	39°22' 5"	39°22'21"
DLA	61°55'40"	61°55'43"	IJC	51° 5'39"	- - -
LAK	75°49'54"	75°49'50"			
ALK	39°13' 9"	- - -			
LKA	64°56'58"	- - -			
ABD	54°42'40"	- - -			
BAC	55°20' 3"	- - -			
ACB	69°57'17"	- - -			
CEH	71°48'15"	- - -			
BHC	56° 0'53"	56° 1'19"			
HCB	52°10'52"	52°10'26"			
GEH	53°30' 7"	53°30' 8"			
BHG	72°54'18"	- - -			
HGB	53°35'34"	- - -			
CAJ	60°11'10"	- - -			
ACJ	57°47' 7"	- - -			
CJA	62° 1'43"	- - -			
JAK	63° 8'55"	63° 8'52"			
AKJ	57° 9'59"	- - -			
KJA	59°41' 7"	59°41' 9"			

S-2 Stake Net: Stake Coordinates, Line Lengths and Azimuths
16-20 March 1957

Stake Positions			Stake Positions		
Coordinates			Coordinates		
Stakes	X	Y	Stakes	X	Y
A	0.	1597.33	G	4.75	-1582.32
B	0.	0	H	-1070.62	-792.66
C	-1141.53	807.92	I	-2813.97	749.97
D	1556.01	639.59	J	-1199.84	2170.15
E	2934.11	249.89	K	-31.76	2962.98
F	1272.95	-1067.83	L	1886.05	2120.42

Lines			Lines		
Length (m)	True azimuths		Length (m)	True azimuths	
AB 1597.33	0°		DE 1432.37	105°49'19"	
BD 1682.34	67°39'18"		EF 2119.94	231°35'55"	
AD 1827.14	121°36'46"		LE 2144.86	330°45'16"	
BC 1398.51	305°17'20"		CI 1673.44	268° 0'56"	
AC 1387.90	235°20' 3"		IH 2327.85	131°30'16"	
DF 1730.72	189°24'47"		IJ 2149.34	48°38'35"	
BF 1661.53	129°59'32"				
DL 1517.29	12°34'12"				
AL 1957.25	74°29'55"				
BH 1332.11	233°29' 5"				
CH 1602.13	177°27'46"				
JC 1363.50	357°32'56"				
AJ 1329.57	295°31'13"				
FG 1372.56	68° 1'13"				
BG 1582.32	179°58'57"				
KL 2094.75	113°43' 4"				
AK 1366.02	358°40' 5"				
GH 1330.55	306°23'23"				
KJ 1411.75	235°50' 4"				

S-2 Stake Net Triangulation
9-17 January 1959

Angles	Observed	Corrected	Angles	Observed	Corrected
DBA	67°37'54"	- - -	FDE	83°35'34"	- - -
DAB	58°22'57"	- - -	DEF	54°14'24"	- - -
ADB	53°59' 9"	- - -	EFD	42°10' 2"	- - -
DBF	62°22'48"	- - -	EDL	93°15'26"	93°15'32"
BDF	58°12'53"	- - -	DLE	41°47'55"	41°47'49"
DFB	59°24'19"	- - -	LED	44°56'39"	- - -
FBG	49°58'53"	- - -	HCI	90°32'36"	- - -
BFG	62° 1'58"	- - -	CIH	43°30'18"	- - -
FGB	67°59' 9"	- - -	IHC	45°57' 6"	- - -
DAL	47° 8'33"	- - -	JCI	89°32'44"	89°32'40"
ADL	70°56'52"	- - -	CIJ	39°22'49"	39°22'53"
DLA	61°54'35"	- - -	IJC	51° 4'27"	51° 4'27"
LAK	75°48'23"	- - -			
ALK	39°14'59"	- - -			
LKA	64°56'38"	- - -			
ABC	54°42'35"	- - -			
BAC	55°18'52"	- - -			
ACB	69°58'33"	- - -			
CBH	71°49' 6"	- - -			
BHC	56° 0'14"	- - -			
HCB	52°10'40"	- - -			
GEH	53°28'41"	53°28'44"			
BHG	72°55'53"	- - -			
HGB	53°35'24"	53°35'23"			
CAJ	60°13'50"	60°13'58"			
ACJ	57°45'39"	57°45'31"			
CJA	62° 0'31"	- - -			
JAK	63° 7' 7"	63° 7'17"			
AKJ	57° 7'55"	57° 7'49"			
KJA	59°44'58"	59°44'54"			

S-2 Stake Net: Stake Coordinates, Line Lengths and Azimuths
9-17 January 1959

<u>Stake Positions</u> <u>Coordinates</u>			<u>Stake Positions</u> <u>Coordinates</u>		
Stakes	X	Y	Stakes	X	Y
A	0.	1597.66	G	2.69	-1582.48
B	0.	0	H	-1070.40	-792.87
C	-1141.19	807.71	I	-2812.88	749.67
D	1555.46	640.11	J	-1196.41	2169.54
E	2933.52	249.52	K	-31.77	2964.16
F	1272.94	-1067.97	L	1885.65	2121.49

<u>Lines</u>		<u>Lines</u>	
Length (m)	True azimuths	Length (m)	True azimuths
AB 1597.66	0°	DE 1432.35	105°49'27"
BD 1682.02	67°37'54"	EF 2120.39	231°35'3"
AD 1826.60	121°37'3"	LE 2145.05	330°46'6"
BC 1398.10	305°17'25"	CI 1672.71	268°0'41"
AC 1387.98	235°18'52"	IH 2327.13	131°30'59"
DF 1731.44	189°25'1"	IJ 2150.44	48°37'48"
BF 1661.08	130°0'42"		
DL 1517.76	12°33'55"		
AL 1957.06	74°28'30"		
BH 1332.07	233°28'19"a		
CH 1602.12	177°28'5"		
JC 1364.45	357°33'21"		
AJ 1326.06	295°32'50"		
FG 1372.04	247°58'44"a		
BG 1582.48	179°59'35"		
KL 2094.41	293°43'29"		
AK 1366.87	358°40'7"		
GH 1330.15	126°24'12"		
KJ 1411.40	235°47'56"		

Strain Rates of S-2 Stake Net

<u>Line</u>	<u>True Azimuth</u>	<u>Strain rate x 10⁻⁵</u>
AB	0° 00' 00"	+11.28
BD	67° 39' 18"	-10.52
AD	121° 36' 46"	-16.17
BC	125° 17' 20"	-12.11
AC	55° 20' 03"	+ 3.12
DF	9° 24' 47"	+22.79
BF	129° 59' 32"	-12.65
DL	12° 34' 12"	+16.93
AL	74° 29' 55"	- 5.32
EH	53° 29' 05"	- 1.64
CH	177° 27' 46"	- 0.33
JE	177° 32' 56"	+38.14
AJ	115° 31' 13"	-144.60?
FG	68° 01' 13"	-21.50
EG	179° 58' 57"	+ 5.53
KL	113° 43' 04"	- 8.88
AK	178° 40' 05"	+34.08
GH	126° 23' 23"	-16.50
KJ	55° 50' 04"	-13.54
DE	105° 49' 19"	- 0.71
EF	51° 35' 55"	+11.62
LE	150° 45' 16"	+ 4.82
CI	88° 00' 56"	-23.89
IH	131° 30' 16"	-16.93
IJ	48° 38' 35"	+28.00

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AUTOBIOGRAPHY

I, Richard Leo Cameron, was born in Laconia, New Hampshire, July 11, 1930. I received my secondary-school education in Quincy, Massachusetts, and Laconia, New Hampshire where I was graduated in June, 1948. During my undergraduate training at the University of New Hampshire, I spent the summer of 1953 at the University of Oslo in Norway. In August 1953 I assisted Dr. Liestøl of the Norsk Polar-institut in studies of glaciers in the Jotunheimen and in Svartisen. The Bachelor of Science degree in geology was awarded at New Hampshire in 1954 and that summer I was assistant glaciologist to Dr. Valter Schytt on an expedition to Greenland. In 1955 I studied glacial geology and glaciology at the University of Stockholm, Sweden. After beginning graduate work in geology at The Ohio State University in 1956 I was invited to join the International Geophysical Year program and I participated as Chief Glaciologist at Wilkes Station in Antarctica. From 1958 to 1960 I assisted Dr. Richard P. Goldthwait in operating the IGY Glaciological Data Reduction Center at Ohio State. In 1961 I accepted a position as Chief of the Geotechnics Branch of the Terrestrial Sciences Laboratory, Air Force Cambridge Research Laboratories.

I am now Assistant to the Director of The Ohio State University Institute of Polar Studies.

I was married to Dorothy Marie Loew in May 1956, and we have two children, Andrew Olaf and Sarah Dorothy.