73-24,063

FAHL, Charles Byron, 1939-
SOME RELATIONSHIPS BETWEEN GLACIERS AND
CLIMATE IN ALASKA.

University of Alaska, Ph.D., 1973
Physics, meteorology

University Microfilms, A XEROX Company, Ann Arbor, Michigan

SOME RELATIONSHIPS BETWEEN GLACIERS AND CLIMATE IN ALASKA

A

DISSERTATION

Presented to the Faculty of the

University of Alaska in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

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Fairbanks, Alaska

May 1973

SOME RELATIONSHIPS BETWEEN GLACIERS AND CLIMATE IN ALASKA

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ABSTRACT

Relationships between climate and glaciers were investigated for three glaciers in mainland Alaska: McCall Glacier in the Brooks Range, Gulkana Glacier in the Alaska Range, and Wolverine Glacier in the Kenai Range. Mean pressure maps (MPM's) were constructed for each glacier for particular seasons and particular climatic conditions that contributed either to the growth of the glacier or to the decay of the glacier. The MPM's were supplemented by classical glacier/climate parameters: long time series of temperature and precipitation at index stations, deviations of the 500 mb height during the ablation period, and 500 mb circulation type frequency variations.

Analysis of the temperature and precipitation records revealed several periods in the past 60 years that were favorable for glacier growth at all three glaciers. The most recent of these periods was the mid-1960's. The overall trend though, has been unfavorable; a return to this trend was noted in the late 1960's. Negative departures of the 500 mb height during the ablation period over Alaska were observed during the three years, 1969-1971. A positive annual mass balance was measured only in 1970 and only for Wolverine Glacier. The period of record of the 500 mb heights, ~1947-1971, has been one of glacier decay; otherwise negative departures would have implied positive balances. Investigation of 500 mb circulation types revealed that the zonal type had frequencies above normal during the 1969-1971 ablation seasons.

The synoptic patterns revealed by the MPM's for summer snowfall on

McCall Glacier resembled other investigator's theoretical July maps for ice age conditions. A low was found near 70° N, 130° W. A northward shift of 2-3 degrees of latitude was noted in the summertime cyclogenetic zone of extreme northwestern Canada. Precipitation at McCall Glacier was enhanced when the Pacific High was stronger than normal, steering cyclones around Alaska into the Beaufort Sea. Ablation on McCall Glacier increased when the Aleutian Low was stronger than normal resulting in generally southerly, drier air at the glacier. Snowfall on Gulkana Glacier was enhanced throughout the year when the mean Aleutian Low was shifted eastward 10-20°. The axis of the low was rotated counterclockwise from W-E about 10°. Ablation increased when the Beaufort Sea High was stronger than normal. Snowfall on Wolverine Glacier was enhanced when the mean Aleutian Low was intensified and shifted eastward to a slightly more southerly position than found for Gulkana Glacier. A stronger than normal Pacific High contributed to increased ablation on Wolverine Glacier in the summertime and reduced accumulation in the wintertime.

The MPM's were representative of the individual maps comprising them 75 % of the time. Cyclone tracks of systems affecting McCall Glacier were constructed for July and August. A combination of tracks with Pacific and Arctic Ocean sources was found. Orographic uplift was noted as an important mechanism for McCall Glacier, increasing the effects of generally moisture-deficient storms there, such as those with Arctic Ocean origins.

MPM's are shown to represent an analytic tool in glacial/climatic investigation. Their use elsewhere and their use in a broader scale than the regional scale is outlined. Examples are given for Alaska whereby MPM's can serve as indicators of conditions in the historic past when favorable/unfavorable glaciation conditions existed. In the 1947-1971 period 8 summers, 5 of which occurred between 1961 and 1967 were found to resemble the MPM for summer snowfall at McCall Glacier. For Gulkana Glacier, 5 summers, including those for 1964 and 1965, were found to resemble the MPM for summer snowfall. Finally, examples are given for each glacier of summers that were similar to the MPM's for hot spells—periods favorable for glacier decay.

ACKNOWLEDGEMENTS

The work reported here was financially supported by the National Science Foundation through their contracts GA-10090 (Mass, Water, and Heat Balance of the McCall Glacier, Brooks Range, Alaska) and GA-28278X (Continuation of a Study on the Ice, Water, and Heat Balance of McCall Glacier.

Appreciation is due the Geophysical Institute, whose facilities and staff contributed in many diverse ways to this project. Thanks are due many people there who have provided constructive criticisms to this study through numerous discussions. Of special assistance has been my advisory committee, chaired by Dr. Gerd D. F. Wendler. The other members were Drs. Carl S. Benson, Sue Ann Bowling, Bernhard Haurwitz, Bjorn Holmgren, and Gunter E. Weller. Drs. Wendler, Benson, and Bowling are due special thanks for providing detailed comments on the manuscript itself.

Through correspondence, I received considerable help from Dr. Roger G. Barry of the University of Colorado; many credits are due him.

Almost all the supporting data for Gulkana and Wolverine Glaciers were supplied by Larry R. Mayo of the U.S. Geologic Survey, Fairbanks, Alaska. Larry also contributed many stimulating conversations, which were appreciated.

Thanks are due the Extended Forecast Division of the National Meteorological Center, Suitland, Maryland, especially Mr. Robert Gelhard, head of their computer applications section, who provided free of charge the magnetic tapes containing the synoptic weather data used to construct the MPM's.

Finally, I would like to extend special thanks to my wife, Patricia, who with two small boys, suffered through many prolonged absences due to field work, and many long nights due to studying. Without her continuing confidence and support this work would not have been possible.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The growth or decay of glaciers is related to the weather and climate. This statement is obviously true in general, as glaciers will not exist in any given area unless the right combination of precipitation and below freezing temperatures occur. However, the exact relationship between the climate and glaciers is still, in general, not completely known. For instance, meteorological variation in the mesoscale range (1-100 km) is not well understood when compared to the synoptic scale. According to Lee (1972), the problem of mesoscale prediction is only now receiving much attention. Since this scale is of prime interest as far as glaciers are concerned, we cannot completely understand the relationship between climate and glaciers until we better understand mesoscale meteorology. Until this occurs we will also not be able to accurately predict the future behavior of glaciers. Fortunately, there is a way in which we can partially circumvent this problem. This is simply to study in great detail the present and/or past relationships between glaciers and the weather and then project these into the future based on long-term trends or periodicities. (The existence of periodicities in the climate is of course, open to some debate, especially concerning exact periodicities (World Meteorological Organization, 1966, p. 3). According to Lamb though, (Sellers, 1972) periods of 2.2, 11, 80 to 100, and 200 years are well documented.)

Even if we cannot accurately predict the future behavior of glaciers (since the future behavior of the climate can only be guessed or approximated) we can learn something of the critical parameters involved and their thresholds, and thus learn something of past glacier activity. Then we can describe the climates that are 'good' or 'bad' for the glacier even if we do not know if and when these climates will reoccur.

When the problem of relating glaciers to the weather first received attention in the late 19th century (Flint, 1971, p. 16) the approach was simply to monitor the advance and retreat of glacier termini (Hoinkes, 1968, p. 3). The advance or retreat of a glacier terminus though, is a function of the glacier size and also the local topography (Ahlmann, 1953, p. 8). If many different sized glaciers in a particular region are either advancing or retreating it does indicate a long-term climatic trend, but if at any given time some termini are advancing while others are retreating the problem of unraveling the climatic fluctuations involved is difficult. A better approach to understanding climatic fluctuations is to monitor changes in the mass of glaciers. The mass balance is largely determined by two factors: the amount of solid precipitation throughout the year, and the heat balance during the ablation (or melting) period (Hoinkes, 1955). These factors in turn reflect the current weather or climate. Theoretically, then, the effect on a glacier of a fluctuation in the climate can be determined almost immediately by a change in the mass balance, while the reaction of the terminus of a typical alpine glacier will lag from 3 to 30 years (Nye, 1960).

1.2 Purpose of Dissertation

Glaciers and their relationship to the climate have not been studied extensively in Alaska. The general purpose of this dissertation is to present the results of a study of this relationship for the Alaska case. Since Alaska is so extensively glaciated the study area has been confined to the area west of 141° W longitude. This area of Alaska is traversed by three major mountain ranges, the Brooks, Alaska, and coastal (composed of the Kenai and Chugach Ranges). These three ranges divide this part of Alaska into four climatic zones: 1) arctic, 2) interior continental, 3) transition, and 4) maritime (cf. Searby, 1968). In each of the three principal ranges, a glacier has been extensively studied during the past four to six years; McCall in the Brooks Range, Gulkana in the Alaska Range, and Wolverine in the Kenai Range. The location of these three glaciers, their respective mountain ranges, and all other geographical names used in this study are shown in Figure 1-1. The area encompassed by the map in this figure will be referred to as the 'Alaska Region'.

1.3 Value of Dissertation

This study will contribute to the overall knowledge of glaciers, climate, and their interactions—especially with respect to Alaska. Specifically, when the circulation patterns and weather systems that contribute either to the growth or decay of glaciers in Alaska have been identified a better understanding of the general circulation and its relationships to glacier growth and decay will ensue. Additionally, identification of such systems will contribute to a better understanding of conditions before, during, and after the last major glaciation. In this respect, the results of this study will serve as 'ground-based truths' for the Alaska region for theoretical studies on circulation patterns

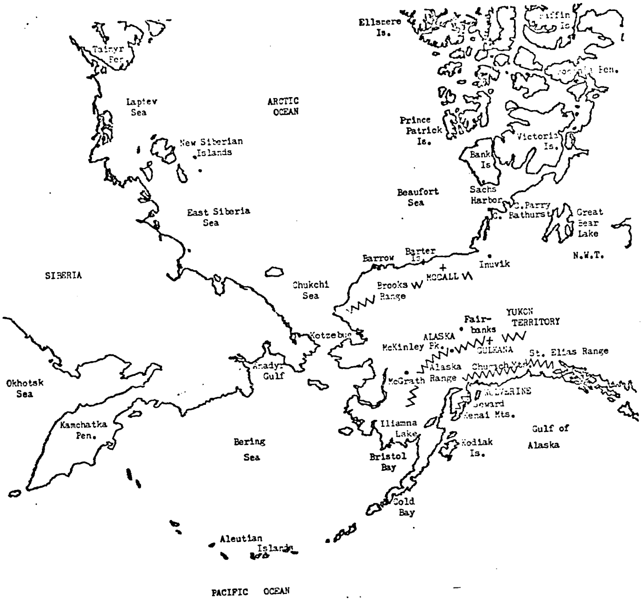

Figure 1-1. The 'Alaska Region'.

in these periods (Lamb and Woodroffe, 1970; Barry, 1973).

1.4 Outline of Dissertation

Two approaches were taken in the research reported in this dissertation. The first was the classical approach, relating glacier fluctuations to standard climatic parameters: a) long time series of temperature and precipitation; b) deviations of the 500 mb pressure surface during the ablation season; and c) frequency variations of hemispheric scale 500 mb circulation types. In the initial stages of this study these were the approaches used; the first two methods have been employed successfully by Hoinkes (1968). Success was limited in the Alaska case though. Thus, the results reported in Chapter 2 (Non mean pressure map approach) serve principally as background and supplementary material for the main body of data.

The second and main approach is termed the Mean Pressure Map (MPM) approach. This approach is presented in Chapter 3. The MPM approach is shown to be a tool of synoptic climatology that can circumvent the problem in Alaska of relatively short records of glacier mass balance fluctuations; the problem that limited the usefulness of the classical approach. A total of 17 MPM's are presented. These show the synoptic patterns that are good or bad for the three glaciers. MPM's for each glacier for a particular season are presented together so that comparisons are facilitated. For each MPM there are two associated or derived maps. The first is the normal map; the 25-year normal sea level pressure map for the particular period (usually 1 or 2 months) that the events constituting the MPM occurred in. The second is the anomaly map.

This map shows the difference in pressure between the MPM and the normal map.

The presentation of all these maps, critical in nature but many in number (17 MPM's, 17 anomaly maps, and 11 normal maps), posed a problem which has been partially solved by assembling them in the appendix. Thus, the MPM's and their associated anomaly maps have been placed in Appendix A, and the normal maps have been placed in Appendix B. Less critical, but nevertheless important, supporting data are presented in Appendices C, D, and E.

In Chapter 4, an extension of the MPM approach is presented. This extension was done for the cases of summer snow on McCall and Gulkana Glaciers and for hot spells at all three glaciers. The purpose of the extension is twofold: a further investigation of summertime conditions, and an illustration of the representativeness of the MPM's. (Are the synoptic patterns revealed in the mean typical of the individual patterns?) The results presented in Chapter 4 then, are analogous to those in Chapter 2; they are basically supplementary. For example, the analysis of storm tracks, briefly reported in Chapter 4 could serve as a foundation for a much broader study. Here, though, this analysis basically serves to further elucidate the MPM's.

The usefulness of the MPM's as ground-based truths for theoretical circulation studies is discussed in Chapter 5.

Finally, in Chapter 6 the principal conclusions to this study are given. The circulation patterns and weather systems that contribute to the growth or decay of glaciers in Alaska are summarized. The use of MPM's as an analytic tool in studying glacial/climatic relationships is given and a specific example is presented for the Alaska case.

CHAPTER 2

NON MEAN PRESSURE MAP APPROACH

2.1 Comparison of glacier activity with long time series of temperature and precipitation

Temperature and precipitation are two of the most widely used climatic parameters, and their fluctuations should be related to variations in glacier mass balances. Since actual meteorological measurements on glaciers are few and far between, the usual approach to the problem is to measure these parameters at nearby localities where long-term records are available. Because of this, and since temperature and precipitation by themselves do not completely describe a particular climate, the results are ambiguous.

A fairly good one-to-one correspondence has been established for a region in the Alps (Hoinkes, 1968, Figure 2) when only the summer season was considered, only high altitude stations were used, and the data were smoothed by taking five-yearly overlapping means. The most favorable summer conditions for glaciers are below normal temperatures coupled with above normal precipitation. Hoinkes found that these conditions were met in 1879-81, 1889-96, 1908-18, 1924-25, and 1955-56 (stipled bars at the bottom of his Figure 2). These periods corresponded closely with periods of known glacier advance in the Alps, viz., 1890-1901, 1906-18, 1926, and 1955 (Hoinkes, 1968, p. 14). Although the advances or retreats of glacier termini are poor indicators of glacier activity, nevertheless, if a sufficiently large percentage are in phase it will give the general tendency correctly (Hoinkes, 1968, p. 4).

Similar graphs have been calculated for the Alaska region (Figures

2-1, 2-2, and 2-3). Because of the dearth of knowledge on Alaska glacier activity, these graphs, for the most part, serve as first approximations to glacier mass balance variations in Alaska. Figure 2-1 serves as a first approximation to glacier activity in the Brooks Range of Northern Alaska. It is interesting to note that the only period indicated here which was favorable for glacial growth was 1960-1967. On McCall Glacier in the Eastern Brooks Range a mean 'annual mass balance'* of -265 mm a^{-1} has been calculated for the 11 year period 1958-1969 (Wendler et al, 1972). This value is within the range (-150/-350 mm a^{-1}) measured during the recent program on McCall Glacier, so that in the period 1921-1959, annual balances were probably even more negative. Further evidence for long-term glacier decline in the Brooks Range is given by the fact that Okpilak Glacier, 15 km to the southwest of McCall (Sable, 1961) and glaciers in the south-central Brooks Range (Hamilton, 1965) have been receding and thinning during the period 1911-1958.

Figure 2-2 serves as a first check on glacier activity in the Alaska Range. It is seen that there have been several periods in the past 60 years when glacier growth might have been expected. Taken as a whole, though, the general trend has been unfavorable for glacier growth. Comparative photographs of Gulkana Glacier, taken in 1910 and 1960 (Sellmann, 1962), showing a general retreat and thinning of the terminus, confirm this. Conditions in the early and mid-1960's were mixed. Mayo (1973) has reported that the annual balance for Gulkana Glacier was positive in 1961, and that in August 1963 aerial photographs showed a very low snowline, probably indicating a positive annual balance. In 1966

* Hereafter referred to as 'annual balance'.

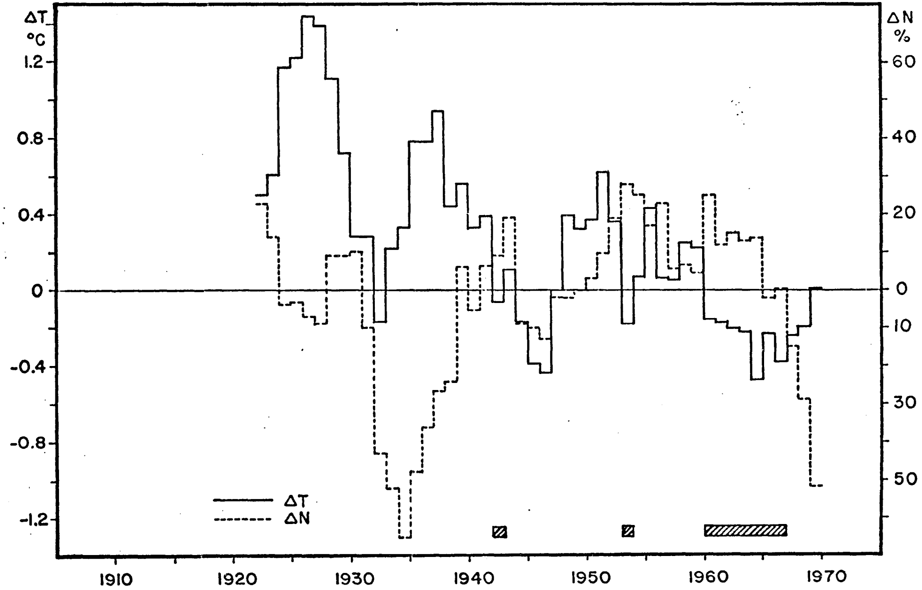

Figure 2-1. Five-yearly overlapping anomalies of temperature and precipitation in summer for Barrow Alaska, 1921-1972, and Barter Island, Alaska, 1948-1972. Hatched bars indicate periods when anomalies were most favorable for glaciation.

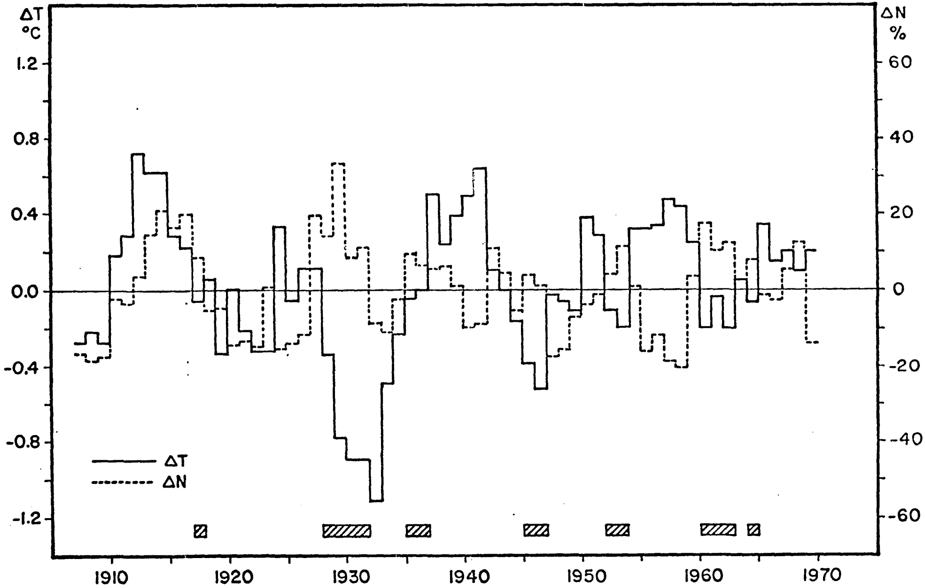

Figure 2-2. Five-yearly overlapping anomalies of temperature and precipitation in summer for Fairbanks, Alaska, 1906-1972, and McKinley Park, Alaska, 1929-1972. Hatched bars indicate periods when anomalies were most favorable for glaciation.

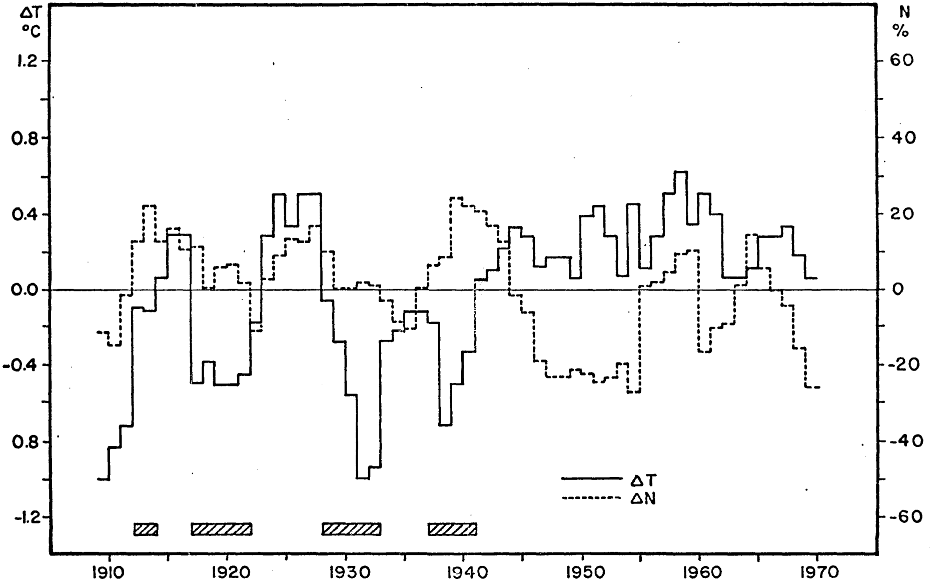

Figure 2-3. Five-yearly overlapping anomalies of temperature and precipitation in summer for Seward, Alaska, 1908-1972. Hatched bars indicate periods when anomalies were most favorable for glaciation.

a small positive balance was measured for Gulkana Glacier (Meier et al, 1971). Almost uniformly, most northern hemisphere glaciers under study during this period experienced one or more positive annual balances, in contrast to the 1940's and 1950's when negative annual balances were the rule. (Positive annual balances did occur in the 1940's and 1950's but they were scattered and the percentage of positive balances was much less than it was in the early and mid-1960's.) In the Alps, for example, Hintereisferner, Kesselwandferner, and Grosser Aletschgletscher were all positive for each hydrological year * from 1965 through 1968 (Hoinkes, 1970, p. 62). Loken (1972) investigated the mass balance history of glaciers throughout the North Atlantic region and found that the only glaciers under study that did not experience at least one positive year in the early to mid-1960's were in the Northern Urals (Grossval'd and Kotlyakov, 1969). In North America, also, most glaciers under study experienced one or more positive annual balances in this period (Meier and Tangborn, 1965; Meier et al, 1971; LaChapelle, 1965; and Ostrem, 1966).

In the late 1960's and early 1970's summertime conditions in the Brooks and Alaska Ranges became less favorable for glacier growth than they had been in the early and mid-1960's. Gulkana Glacier experienced negative annual balances from 1967 through 1969 and again in 1971 (Mayo, 1973). McCall Glacier has not been positive in any year since the current program was started in 1969. The situation elsewhere was similar. Most glaciers in Scandinavia, for example, turned negative in 1969 (Loken, 1972), while the Ward Hunt Ice Rise and Decade Glacier in the Cana-

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* A hydrological year (HY) runs from October 1 of the previous year through September 30. Thus the 1965 HY ran from October 1, 1964 through September 30, 1965.

dian Archipelago have experienced mostly negative annual balances since 1967.

Figure 2-3 serves as a first check on glacier activity in the Kenai Mountains of coastal south-central Alaska. In so far as the coastal station of Seward reflects conditions on nearby glaciers it is seen that the favorable periods for glacier growth occurred more than 30 years ago. Conditions were almost favorable in the 5-year period centered on 1965—a period that was also favorable elsewhere in Alaska, and a period when large positive annual balances were recorded in other regions. For example, in the 1965 HY Hintereisferner had an annual balance of 925 mm * (Hoinkes, 1968), its largest positive balance in 16 years of measurement; Storglaciaren had an annual balance of 430 mm (Loken, 1972), its third largest positive balance in 25 years of measurement; and the Ward Hunt Ice Rise had an annual balance of 200 mm (Hattersley-Smith and Searson, 1970), its largest positive balance in 10 years of measurement.

Actual data from Wolverine Glacier (about 40 km NE of Seward) have shown that the summer temperatures are warmer than those of Gulkana Glacier in the Alaska Range or McCall Glacier in the Brooks Range. With the possibility of summer snow reduced the importance of summer as a critical period is decreased and Figure 2-3 is not as accurate a first approximation for glacier growth in the Kenai Mountains as Figures 2-1 and 2-2 are for the Brooks and Alaska Ranges respectively. The situation in the Kenai Mountains might be comparable to that found for the

* Annual balances are reported in units of water equivalent. Thus an annual balance of +200 mm indicated that a glacier gained a mass equivalent to 200 mm of water times the area of the glacier.

Blue Glacier in the Olympic Mountains of Washington. There, "The annual mass budget [balance] is strongly influenced by altitudes of the freezing level during spring and autumn storms, for these determine whether the heavy precipitation falls as rain or snow," (LaChapelle, 1965, p. 609).

It has been seen that long-term temperature and precipitation records and their fluctuations can be related to glacier annual balance fluctuations. They have been especially useful in providing a qualitative insight into past glacier activity. However, in so far as quantitative insights have not been provided and further elucidation of the climate/glacier relationship has not been given, they are limited in their usefulness.

2.2 Comparison of glacier activity with deviation of the 500 mb pressure surface during the ablation season

Hoinkes (1968) found that negative deviation of the 500 mb pressure surface during the summer ablation season was correlated with positive annual balances. Similarly, a positive deviation was correlated with negative annual balances. According to Hoinkes (1968, p. 11) the lower than normal 500 mb surface was an indication of more cyclonic weather than normal. Thus there was more cloudiness and snow than normal. Likewise, the higher than normal 500 mb surface was an indication of less cyclonic weather, and thus less cloudiness and snow.

Similar investigations have been carried out for the Alaska region for the 1969, 1970, and 1971 ablation seasons. Figure 2-4 shows the deviations from normal of the 500 mb surface over the Alaska region for the 1969 ablation season. All three glaciers under consideration experienced negative annual balances while the deviation from normal of the 500 mb

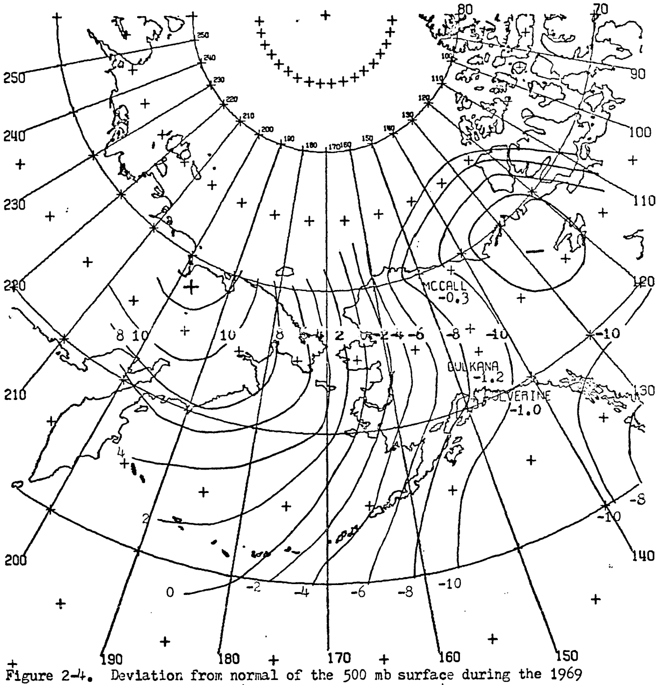

Figure 2-4. Deviation from normal of the 500 mb surface during the 1969 ablation season (June + 2 x July + August) in geopotential decameters (gpdm). Annual mass balances in meters of water.

surface was also negative. Figure 2-5 shows the deviation from normal of the 500 mb surface for the 1970 ablation season. Again, the Alaska region was covered by an area of negative 500 mb height departures. These departures were greater than during 1969. Wolverine Glacier experienced a positive annual balance, while Gulkana Glacier was in equilibrium. McCall Glacier, however, was again negative although not as much as it was the year before. Figure 2-6 shows the deviation from normal of the 500 mb surface for the 1971 ablation season. The pattern for this year was much different than the previous two years. Over the glaciers being studied the 500 mb height deviations were negative but only slightly so. McCall Glacier again had a negative annual balance while Gulkana and Wolverine Glaciers were close to equilibrium. Since the 500 mb deviations were the least negative of the three years in 1971 it was expected that the annual balances for 1971 would be the most negative. However, this did not occur, and 1971 annual balances for all three glaciers fell between the 1969 and 1970 values. The results then, are not as conclusive as Hoinkes (1968) found for Europe. In the cases he investigated, a negative deviation of the 500 mb height for the ablation period was associated with positive annual balances. There are two possible explanations why the same sort of association was not found for the Alaska case. First, the ablation season, June through August, might not be as dominant a period for the annual balance as it is in Europe. The accumulation season, September through May, may have been equally important, if not more important in these three years. The second explanation is related to the averaging period of the 500 mb heights. If glacier activity has been stable during the averaging period a zero departure implies a zero annual balance.

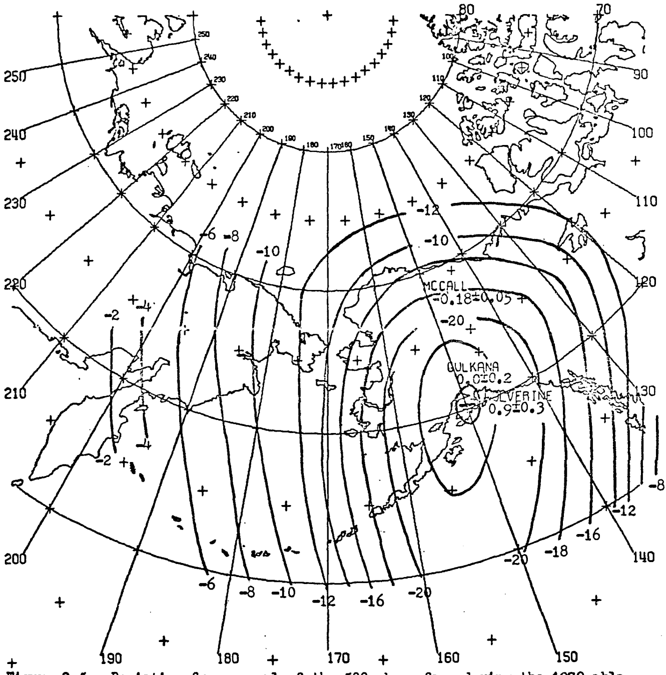

Figure 2-5. Deviation from normal of the 500 mb surface during the 1970 ablation season (June + 2 x July + August) in geopotential decameters (gpdm). Annual mass balances in meters of water.

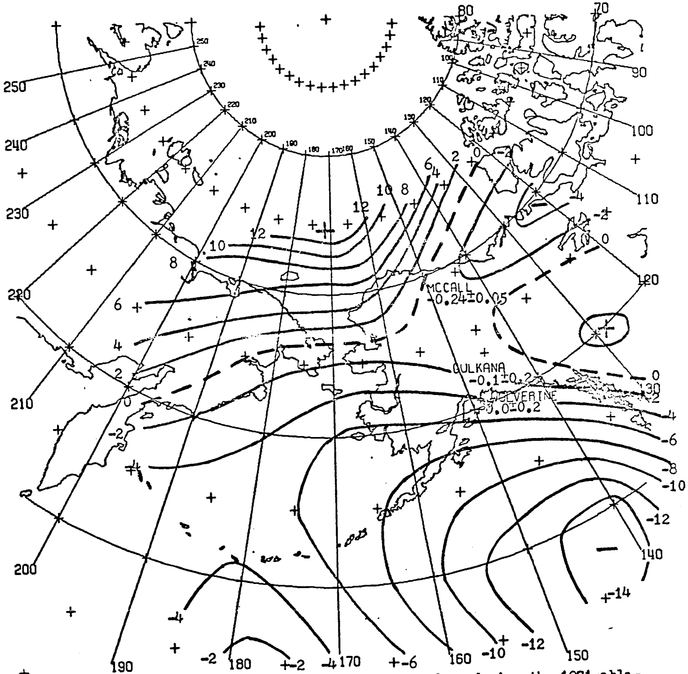

Figure 2-6. Deviation from normal of the 500 mb surface during the 1971 ablation season (June + 2 x July + August) in geopotential decameters (gpdm). Annual mass balances in meters of water.

Likewise, a negative departure implies a positive annual balance. This is the situation that Hoinkes found. In the Alaska case though, negative annual balances were found with zero and even negative 500 mb height departures. This implies that glaciers have declined over the length of the 500 mb averaging period. Also, in this case, the departure that implies a zero annual balance will be a negative one.

A further complexity might be that each of the three glaciers under consideration might have different threshold values. The three years of data has not been enough to establish whether or not there is a linear relationship between annual balances and the 500 mb surface deviations during the ablation period. When more data becomes available statistical tests might be applied to test whether any correlations exist.

2.3 Comparison of glacier activity with frequency variations of hemispheric scale 500 mb circulation types

The ultimate object in the study of climatic and glacial fluctuations should be to relate the glacial fluctuations to those of the general circulation. This is desirable since fluctuations of the general circulation are basic in nature, large in scale, and reflect fluctuations of the global climate. Specifically, it is desirable to find out what happens to glaciers in Alaska due to fluctuations of the general circulation. A convenient way to study fluctuations of the general circulation is to determine types of circulation patterns and study the frequency variations of the different types. A particularly simple and useful typing scheme is that of Vangenheim and Girs (Girs: 1958, 1963a, 1963b, 1966a, and 1966b). Investigating the flow at the 500 mb level, Vangenheim in 1939 (Girs, 1966b) identified three main patterns of atmospheric circulation for the Atlantic-European sector ($\sim 60^\circ$ W to 40° E): a western type 'W', an eastern type 'E', and a meridional type, 'C'. Girs, in 1948, showed that three similar circulation patterns occur in the North American-Pacific Ocean sector of the Northern Hemisphere ($\sim 180^\circ$ W to 80° W) (Girs, 1966b): a zonal type, 'Z', and two meridional types,'M1' and 'M2'. Based on the author's own cataloguing, the pertinent features of the three North-American-Pacific Ocean types, with special emphasis on Alaska, are as follows: The zonal type, Z, is characterized by small amplitude waves generally between latitudes 40° and 60° N. Frequently, the weather in Alaska is colder than normal during the Z type, although not excessively so. Also, stronger than normal high latitude flow at the 500 mb level is sometimes observed during the Z type, bringing cyclonic weather to the north coast of Alaska even though the main storm track remains to the south of Alaska. Meridional type M1 is characterized by an extension of the North Pacific High over Alaska. The most favored position of the axis of the 500 mb ridge lies just west of Alaska near the 170° W meridian. The Aleutian Low is weak and shifted to the west. This type is accompanied by very cold dry weather at the surface in winter. Meridional type M2 is the opposite of M1 with a cold trough from the Arctic instead of a warm ridge from the south. At the surface the Aleutian Low is very prominent, dominating the picture for the whole North Pacific. The trough line, like the ridge line of type M1, has a preferred position along the west coast of Alaska. Consequently, the flow of air over Alaska is from the south bringing warm weather in all seasons. Neglecting the effects of topography, this type can bring even more moisture and precipitation to mainland Alaska than the Z type.

In this study the investigation was limited to the summer months only from 1969 to 1971. Also, the only glaciated area of Alaska that was studied with respect to Girs' circulation types was that of the Brooks Range. Table 2-1 summarizes the catalogue of daily types found for the whole northern hemisphere for the summer months of 1969-1971. Also shown here are the averages for this three year period, the long period normals and the ratio of the three year averages to the long period normals. Perhaps the most interesting result was the normality of the Atlantic-European types versus the abnormality of the North American-Pacific types. For each of the three years types Z and M2 were substantially above normal while M1 was substantially below normal. Although three years is too short a time to make any conclusions it is interesting to note that such a distribution of types is also not duplicated as normal for any of Girs' circulation epochs (Girs, 1966a). The normals for these epochs and their ratio to the long-term (1900-1960) normals are presented in Table 2-2.

Girs (1966b) has tabulated the summer (May-September) months from 1932-1963 when the frequency of circulation types W, E, or C exceeded 20 days. Since these tabulations include the frequencies of all six circulation types it is possible to make a partial list of those months when the frequencies of Z, M1, and M2 exceeded 20 days. During the 1969-1971 summer months only the Z circulation type had monthly frequencies of 20 days or more. Table 2-3 is a list of these months along with the partial list of months in the 1932-1963 period when Z type frequency was 20 days or more. Also shown here are the temperature and precipitation anomalies

TABLE 2-1

Frequency in days of Girs 500 mb circulation types during the summer months 1969-1971

Type	1969	1970	1971	Average	Normals	Average/Normal
Z	58	65	42	55.0	32.4	1.70
M1	12	9	14	11.7	46.8	.25
M2	22	18	36	25.3	12.8	1.98
W	30	34	36	33.3	32.3	1.03
C	39	35	29	34.3	29.2	1.17
E	23	23	27	24.3	30.5	.80

TABLE 2-2[a]

Average summertime (June - August) frequencies in days and the ratio of these averages to the 1900 - 1960 normals for Girs' 500 mb circulation types during different circulation epochs

Type	Epoch							
	1900-1928		1929-1939		1940-1948		1949-1960	
	Freq.	Ratio	Freq.	Ratio	Freq.	Ratio	Freq.	Ratio
Z	33.2	1.02	29.2	.90	34.2	1.06	31.3	.97
M1	51.5	1.10	50.4	1.08	35.5	.76	40.9	.87
M2	7.3	.57	12.4	.97	27.3	2.13	19.8	1.55
W	32.3	1.21	29.2	.90	24.5	.76	24.5	.76
C	29.2	1.05	21.6	.74	34.6	1.18	28.5	.98
E	30.5	.73	41.2	1.35	32.9	1.08	39.0	1.28

a The data for this table was abstracted from various figures and graphs in Girs' 1963b paper.

TABLE 2-3

Girs' circulation type frequency and temperature and precipitation anomalies[a] at Barrow and Barter Island for those months (June - August) when 'Z' type frequency exceeded 20 days

		Type						Anomaly			
								Temperature		Precipitation	
Year	Month	Z	M1	M2	W	C	E	Barrow	Barter Island	Barrow	Barter Island
1932	July	20	11	0	0	19	12	0.7	-	-12.5	-
1939	August	22	9	0	3	0	28	0.3	-	-12.5	-
1940	August	31	0	0	2	0	29	0.4	-	- 9.7	-
1943	August	31	0	0	21	10	0	-0.2	-	- 5.3	-
1946	July	31	0	0	5	21	4	0.1	-	-16.0	-
1955	August	28	3	0	0	9	22	-3.2	-	7.1	59.7
1959	July	27	4	0	5	5	21	-1.4	-1.3	16.5	27.4
1960	August	22	9	0	6	5	20	-2.1	-1.7	14.0	- 9.4
1961	August	20	2	9	19	3	9	-1.4	-1.0	10.4	1.0
1969	July	21	4	6	13	11	7	-2.4	-1.4	-10.9	0.5
1969	August	21	8	2	7	14	10	-3.4	-3.6	- 0.5	11.4
1970	June	20	2	8	4	24	2	-0.1	-0.4	- 8.6	-10.2
1970	July	21	5	5	14	2	15	-0.7	-1.3	-15.8	-14.2
1970	August	24	2	5	16	9	6	-1.4	0.3	-14.0	-14.0
1971	August	21	3	7	19	10	2	-2.4	-2.4	-14.0	-16.0
Sum		360	62	42	134	142	187	-17.2	-12.8	-71.8	36.2
Average		24	4	3	9	9	12	-1.1	-1.4	- 4.8	4.0

[a] Temperature anomalies are given in degrees Celsius and precipitation anomalies in millimeters of water. The 1931-1960 Normals were used. Data was abstracted from NOAA (1971a and 1971b).

for Barrow and Barter Island for these months. These anomalies serve as first approximations to glacier activity in the Brooks Range for these months. The average temperature and precipitation anomalies shown in Table 2-3 reflect the relative increase in cyclonic activity that occurs when the frequency of Z type circulation increases. With such an increase it would be expected that glacier growth would be enhanced. Actually, this was difficult to ascertain as the mass balance for the summer months only was not calculated, so that the effect of the ablation period balance on the annual balance was not known. Also, this effect no doubt varies from year to year. Since McCall Glacier has been negative during 1969-1971, it is concluded that a high frequency of Z type weather in the summer is not a sufficient condition for positive annual balances.

It has been shown that some relationships between glacier activity and the frequency of 500 mb circulation types can be made. Since a catalogue of daily types from 1881-1962 exists * some statistical inferences concerning current frequencies can be made. However, the subjectivity involved in the typing limits the usefulness of this method.

2.4 Summary

All of the classical methods presented here have made clearer the relationships between the weather/climate and glacier activity—growth or decay in Alaska. However, one significant drawback has been encountered with each method. This drawback is the lack of long-term records of glacier annual balances. Since only poor approximations of unmeasured annual

* According to Barry(1972), this catalogue has been published as follows: Bolotinskaya, M., and Ryzakov, L., 1964: Catalogue of macrosynoptic processes according to the classification of Vangenheim, 1881-1962, Arkt. i Antarkti. Nauch. Issled. Inst., Leningrad, 158 p.

balances can be made * the efficacy of these classical methods to explain the relationship between climatic and glacier annual balance fluctuations will not be increased until much longer period records of annual balances are obtained.

* According to Mayo(1973), improvements in aerial photography methods have been made that will allow (at least in the case of glaciers with a high activity index (cf. Meier et al, 1971)) more accurate annual balances to be obtained in the future with actual occupation of the glacier taking place only once every ten years.

CHAPTER 3

THE BASIC MPM APPROACH

3.1 Introduction

The problem of relating fluctuations of climate to glacier mass balance fluctuations when long-term records of mass balances are lacking is circumvented with the MPM approach. This approach or method can be classified as a synoptic climatological tool. Many meteorological investigations employ synoptic climatological methods, but when these methods include the use of mean pressure maps, standard time periods, generally a month, are employed. Barry and Fogarasi (1968) departed from this practice in their studies relating to glaciation of Baffin Island. The general method they employed there has been used in the current study with certain modifications and refinements.

The general method involves averaging the sea level pressure for those days when a specified climatic condition occurs. Climatic conditions are chosen which are deemed either good or bad for the health of glaciers. Specification of the climatic conditions also depends on the length of the climatic record at or near a particular glacier. Suitable threshold values are chosen to give a statistically useful number of events for each condition or case. The resulting map shows the mean pattern of circulation features such as highs and lows, baroclinic zones and storm tracks, and the resultant geostropic wind flow.

This map can be used by itself as a partial explanation of either the growth or decay of a particular glacier. That is, for whatever climatic condition is chosen, correct interpretation of the MPM will show the resultant wind speed and direction that occurs for such a condition; the position of storm tracks and baroclinic zones; and the positions of 'centers of action' (Namias, 1950). For example, Figure A-13a* shows a mean low centered near 62° N, 154° W with a trough of low pressure extending from this low towards the southwest. Thus, the preferred storm track for this condition is along this trough with the storms stagnating in southwestern Alaska. Also in the figure, the bending of the isobars in the area of the Laptev Sea probably indicate the furthest extension of the trough that extends to the northeast from the Icelandic Low.

The significance of the features manifested in the MPM's is further elucidated by comparison with other mean maps. Specifically, comparison with the normal maps for the time period of the particular climatic condition being studied will bring out the relative intensities of systems, the magnitude of the shifts in location of centers of action and other circulation features. The departures from normal of the sea-level pressures of the MPM can be vividly shown by constructing an anomaly map. Knowing the standard deviation of the pressure, areas where the anomalies are significant at prescribed levels can be shown also.

3.2 Methods

3.2.1 Selecting climatic conditions

The first step in the MPM approach is the selection of climatic conditions that are either good or bad for the health of a glacier. Some

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* The MPM's and their associated anomaly maps are presented in Appendix A, p.104.

subjectivity is involved in this process but in general most conditions are relatively straightforward. When a glacier gains mass its health is by definition good. Thus, snowfall at any time of the year is good for the glacier. Another climatic condition that is good for the glacier is a day without sunshine. For example if the number of such days during the summer ablation period is greater than normal the health of the glacier should be improved due to reduced ablation. However, the subjectivity implied in this condition is clearly greater than that of snowfall and for that reason sunless days were not considered.

When the glacier loses mass its health is by definition bad. For the glaciers considered in this study loss of mass or ablation was generally confined to the period from June through August. On McCall Glacier, the ablation period was slightly shorter than this while on Wolverine Glacier, it was slightly longer. Bad days were selected on the basis of daily mean temperatures with the warmest days considered the worst for the glacier's health. Previous studies (cf. Paterson, 1969, chap. 4), have found solar radiation the most important term in the heat exchange between glacier and atmosphere, with convection or the transfer of sensible heat the second most important term. The latter is more effective in providing heat to the glacier surface, and thus melting snow or ice, the higher the temperature. Therefore, warm days were selected as the climatic condition that was bad for the glaciers.

According to Meier et al. (1971) Wolverine Glacier should be classified as temperate with a strongly maritime glacier environment. McCall and Gulkana Glaciers would be classified as sub-polar (cf. Paterson, 1969,

p. 7) with McCall Glacier having the stronger continental environment. Consequently, the average annual precipitation amounts vary considerably between the three glaciers, and different thresholds of significant snowfall were chosen for each glacier. On McCall Glacier a snowfall in 12 hours greater than or equal to 2.5 mm water equivalent (w/e) was considered significant. When precipitation at Barter Island (80 km north of McCall Glacier) was substituted for precipitation at McCall Glacier, the threshold was 1.3 mm (0.05 inches) w/e in 12 hours. At Gulkana Glacier, the threshold was 7 mm w/e in 12 hours while at Wolverine Glacier it was 10 mm w/e in 12 hours. Precipitation variability has been observed to be quite large in the Wolverine Glacier basin, with much of the accumulation zone of the glacier receiving almost three times as much precipitation as the index precipitation gauge. Precipitation variability has been observed to be less for the Gulkana and McCall Glacier basins so that the threshold values for significant snowfall given above are more representative of amounts that actually fell in the accumulation zone for those glaciers. The index precipitation stations for all three glaciers were below the equilibrium line so that snow could occur in the accumulation zones while rain was occurring at the index stations. A lapse rate of $0.65^{\circ}\ 100m^{-1}$ was therefore assumed. A precipitation event was considered a snowfall event in the accumulation zone if the adjusted accumulation zone temperature was $\leq 1.7^{\circ}C$. Studies have shown that below this temperature, precipitation occurs as snow 90 % of the time (U.S. Army Corps. of Engineers, 1956, p. 55).

Different temperature thresholds were also used for the three glaciers in the case of hot spells. An attempt was made to consider about the same frequency of hot days at each glacier. Consequently, threshold values for daily mean temperatures of 13.0° C, 12.0° C, and 8.5° C for Wolverine, Gulkana, and McCall Glaciers respectively were chosen. The higher temperatures found at Wolverine and Gulkana Glaciers partially reflect the greater accumulations that occur there, and the higher energy [temperature] inputs required for melting.

3.2.2 Constructing the MPM

The area selected for coverage by the MPM's was chosen large enough to show the most important circulation features. A larger area, covering the whole northern hemisphere, for instance, could have been employed, but it was felt that the effect of anomalies at a large distance, such as those in the Atlantic Ocean, on glacier activities in Alaska would be quite small. On the other hand, a smaller area such as mainland Alaska would not show enough of the important circulation patterns. On some of the anomaly maps that were constructed, the most significant anomalies occurred outside mainland Alaska.

The Extended Forecast Division (EFD) of the National Meteorological Center has established a program whereby the pressure data for the whole northern hemisphere are extracted twice a day (0000 GMT and 1200 GMT) and placed on magnetic tape. For this study they provided data for the period January 1, 1947 through June 21, 1972. Pressure has been gridded for those intersections where both latitude and longitude are evenly divisible by 10, and also by those intersections both of which end in digit 5. This grid was particularly useful for the Alaska region as the effective grid spacing is almost as small as the station spacing; most synoptic scale features were therefore revealed. Being on magnetic tape these data were easily handled by high-speed computer. Since the data covered the whole northern hemisphere a special program was written to extract the data for the Alaska region. The number of grid points included in the Alaska region was 121. A second program was written that manufactured a map with polar stereographic projection. The main program averaged the pressure data at each grid point and prepared a plot. This program was written to accept one title card and an indefinite number of data cards. Each data card gives the data and time (either 0000 GMT or 1200 GMT) of a single event of a particular case. For each case the deck of data cards was inserted in the main program deck and the program was run on the computer. The polar stereographic map was plotted, and then the programmed contours were plotted producing an overlaid map, the MPM for that case.

3.2.3 Interpreting the MPM—Constructing the associated anomaly map

Methods of interpreting the MPM itself were straightforward. The wind near a glacier in question and the identification of the positions of circulation features such as highs and lows, troughs and ridges, etc., involved only elementary meteorology. Identification of mean storm tracks and frontal zones required some experience; a knowledge of typical synoptic patterns and their typical movements throghout the year was helpful.

Anomaly maps represent a further method of interpreting MPM's. Several difficulties arose in constructing these maps, the first of which was deciding which of several available normals to use. The normals that were selected were preliminary 25-year normals (1947-1971) provided by the Extended Forecast Division. Monthly values for this period were also provided so that standard deviations could be calculated (these had not yet been calculated by the EFD for the new 25-year normals). Some minor inconsistencies between the monthly values and the 25-year normals appeared, but these were resolved by correcting the 25-year normals.

O'Connor (1961) has presented normals for the 12-year period 1947-1958 and discussed the differences between these and the normals in use at that time—normals that were based on data prior to 1950. The new 25-year normals differed from the old 12-year normals only slightly in the Alaska region. The new October normals, for example, show the Aleutian Low slightly weaker than before, but otherwise there has been no change. In February, the reverse has occurred with the two centers of the 1947-1958 Aleutian Low having merged into one center and the overall intensity of this low having increased. Another minor change has been the reversal of some features in the Arctic Ocean between July and August. In the 1947-1958 normals there was a weak low near the North Pole on the August chart but none on the July chart. The new normals show the opposite with the weak low appearing on the July chart but not on the August chart. However, caution must be exercised in interpreting features in the high Arctic Ocean; the new normals for 85° latitude grid points were reduced from the relatively short period of 1964-1971. An additional problem in this area is sparse data and a tendency by analysts to draw what they think should be there (cf. U.S. Weather Bureau, 1952).

In general, a MPM represents the synoptic situation for a climatic condition for a particular season or part of a season. Therefore, a second difficulty arose in choosing the particular normal map to compare the

MPM with in order to construct the anomaly map. In some cases the selection of the normal map was straightforward. For example, the condition of summer snowfall on McCall Glacier had cutoff dates of June 15 and August 15. Since the individual dates of snowfall during the study period were spread fairly evenly throughout this period the use of July as the normal month was readily justified. When such a choice was not apparent a special scheme had to be employed to choose the normal period. Each event of a case has a 'true 30-day normal' period centered on the date of that event. Generally this period includes parts of two months. Thus, an event date of January 20 has a true 30-day normal period of January 5 through February 5. An equation for this normal can be written as follows:

January 20 normal = 25/30 (January normal) + 5/30 (February normal)
= 0.83 (January normal) + 0.17 (February normal).

The 'normal equations' for each event of a particular case were summed and averaged The average equation was operated on a reduced grid of 38 points producing a set of preliminary case normals. These normals were then compared to the 38 corresponding monthly normals and simple combinations of monthly normals in order to arrive at the final case normals. Standard monthly normals or simple combinations of them were necessary as standard deviations could not readily be obtained otherwise. An example of this procedure was the case of winter snowfall at Gulkana Glacier. For this condition winter was defined as the period from November 15 to March 15 and the case normal equation was found to be:

case normal = 0.11 (November normal) + 0.18 (December normal) +
0.26 (January normal) + 0.38 (February normal) +
0.07 (March normal).

It was then found that the resulting preliminary case normals were closest in form to normals formed by averaging the December and February normals. These normals (February + December normals/2) thus became the normals from which an anomaly map was constructed for the condition of winter snow at Gulkana Glacier.

A third difficulty arose in deciding what areas on the anomaly map were significant at the 95 % confidence level. A straightforward application of the 'Student's' t-test was not possible since the standard deviation of the daily pressure as a function of time and space for the Alaska region was not known. If it is assumed that there is no persistence in pressure readings from one day to the next a well known formula in statistics (e.g., Brooks and Carruthers, 1953, p. 44) could have been applied to the standard deviations, σ_m, calculated from the 25 monthly values to yield the standard deviation of daily pressure ($\sigma = \sigma_p$):

$$\sigma = \sqrt{30}\ \sigma_m . \qquad (1)$$

Application of this formula yielded standard deviations of daily pressure as large as 40 mb for some localities in the winter months. Standard deviations on this order are obviously too high and the explanation was that pressure persistence is significant and could not be neglected. Brooks and Carruthers (1953, p. 326) have given a modified version of equation (1) which is applicable when persistence is of the first-order linear Markov form. When this equation was applied to the situation here, the following slightly modified form resulted:

$$\sigma = \sigma_m \sqrt{30} \left[1 + \frac{2r}{1-r} \left(1 - \frac{1}{30} \cdot \frac{1}{1-r} \right) \right]^{-\frac{1}{2}} . \qquad (2)$$

where r is the one-day lag autocorrelation coefficient. The larger this coefficient is the greater the persistence is and vice-versa. Brooks and Carruthers (1953, p. 44) have given a coefficient of 0.68 for Kew Observatory in the winter months but indicate elsewhere (p. 323) that "... the autocorrelation coefficients between pressures on successive days varies greatly from year to year". For the Alaska region, Klein (1951) has published data concerning r as well as σ_p, the standard deviation of the interdiurnal pressure change and σ_p (or simply σ), the standard deviation of the daily pressure (in practice the standard deviation of the daily pressure anomaly). Klein has only given maps of r for the winter and summer. In addition he has not shown the value of r for Northern Asia west of Eastern Siberia. Part of the Alaska region is in this uncharted area so Klein's maps were extended here. Also, the r values for spring and fall were interpolated from the winter and summer values based on a linear change from season to season.

The standard deviations of daily pressure obtained from equation (2) using the extended version of Klein's r charts agree fairly well with Klein's σ_p charts for the winter period (cf. Figure C-4, and Klein's Figure 5) but not so well for the summer period (Figures C-1 and C-2, and Klein's Figure 6). It is felt that the geographical distributions of σ presented here are more accurate, at least with respect to the 25-year period 1947-1971. In Klein's paper, $\sigma = \sigma(r, \sigma_p)$ while here $\sigma = \sigma(r, \sigma_m)$. The quantity σ_m is known with more accuracy than either r or σ_p so that the combination of σ_m and r in equation (2) has yielded a more accurate σ than that yielded by the combination of r and σ_p in Klein's equation (2). In Figure C-3, the geographical distribution of σ for October is given. It is interesting to note that the differences between the October and

December (Figure C-4) charts are similar in form to those found between the October and December normal charts for sea level pressure (Figures B-9 and B-10).

When N' is substituted for the factor of σ_m in equation (2) the equation for 'Student's' t-test can be written:

$$t = \frac{(\bar{x}-u)\sqrt{N''-1}}{\sigma} = \frac{(x-u)\sqrt{N''-1}}{\sqrt{N'}\ \sigma_m} , \qquad (3)$$

where $\bar{x}$ is the case mean, u is the normal mean, N' is the effective sample size *, and N" is the number of random samples (= degrees of freedom) in the particular case. In practice the ratio $\frac{\bar{x}-u}{\sqrt{N'}\ \sigma_m}$ was calculated. When this exceeded $\frac{1}{\sqrt{N''-1}}\ t_{.05,N''}$ **, the case mean was significant at the 95 % level. Similarly, if this ratio exceeded $\frac{1}{\sqrt{N''-1}}\ t_{.01,N''}$, the case mean was significant at the 99 % level.

For r = 0.75, N' was found to be 4.84. Thus in a month there would be about six random or independent samples. Accordingly, the number of events or samples, N, in a particular case was reduced whenever two or more events fell within N'/2 days of each other. For example, in the case of hot spells, persistence was quite strong, and the ratio N/N" was on the order of 3 (2.3 for McCall Glacier, 3.1 for Gulkana Glacier, and 3.0 for Wolverine Glacier).

* N' = N'(m) where m is the number of days making up the 25 periods from which σ_m is calculated. Usually m = 30, but in some cases 60-day periods were used. (When r = 0, N' = m.)

** The subscript 0.05 is the probability that t is as large or larger than the tabular value by chance.

3.3 Discussion of the MPM's

3.3.1 Summer snowfall

Whenever snow fell in the summer the normal ablation process was retarded due to the high albedo of the fresh snow. For this reason, ablation season snowfall was considered a more critical climatic condition than accumulation season snowfall. Summer snowfall is expected on McCall and Gulkana Glaciers; its occurrence is more common on the former. On Wolverine Glacier though, it is virtually nonexistent at the present time. Thus, MPM's for this climatic condition were made for McCall and Gulkana Glaciers only.

McCall Glacier

Figure A-1a is the MPM (# 1) for summer snowfall on McCall Glacier. The summer/ablation season was defined as 15 June - 15 August and data from three complete summers, 1969-1971, and one partial summer, 1972, were used. Perhaps the most significant feature on this map is the closed 1006 mb low just to the east of McCall Glacier. Also significant is the broad area of low pressure extending to the north from this low. The mean geostrophic wind for the glacier is from the WNW. A geostrophic wind with a northerly component was found in virtually each event comprising the MPM's for snowfall on McCall Glacier. Several mechanisms were responsible for this. First, there was the effect of local topography. Because of the N-S orientation of McCall Glacier, with the terminus to the north, the important orographic effect would only operate when the wind had a northerly component. Secondly, the Arctic Ocean which can serve as a source of moisture, especially during the July-September period, is located to the north. Thirdly, storms that originate to the south, with moisture derived either from interior wetlands or from the Pacific Ocean, have much of their moisture removed in passing over the main bulk of the Brooks Range which lies to the south of McCall Glacier. That is, winds with a southerly component lose much of whatever moisture they contain before they reach McCall Glacier.

The position of the low to the east in MPM # 1 indicates that the significant snowfalls occurred after passage of cyclones and troughs. In general, temperatures would be colder to the rear of these cyclones and troughs so that the occurrence of solid rather than liquid precipitation would be enhanced. Another reason for the position of the mean low to the east was the occurrence of cold type occlusions with a warm front aloft and to the rear of the surface trough. This type of occlusion is to be expected in the summer in this region; the North Slope of Alaska is usually warmer than the Arctic Ocean so that the air on the leading side of an occlusion is warmer than that behind giving rise to the cold type occlusion.

A comparison with the normal July chart (Figure B-5) and the anomaly map (Figure A-1b) show that the normal weak high centered near Cape Bathurst ($\sim 70^\circ$ N, 130° W) has been replaced by a low. Additionally, the weak low near the North Pole on the normal chart has intensified and merged with the Cape Bathurst Low on the MPM. Thus, all of the western Arctic Ocean is covered by a negative anomaly, indicating more cyclonic activity than normal. The center of this anomaly coincides with the MPM low near Cape Bathurst. This large negative anomaly area is partially compensated by a positive anomaly area over most of northeastern Siberia.

Gulkana Glacier

MPM # 2 (Figure A-2a) shows the synoptic pattern for the condition of summer snowfall on Gulkana Glacier. A weak trough of low pressure is shown extending eastward from southwestern Alaska in an arc to Great Bear Lake in Canada. The axis of this trough lies to the north of Gulkana Glacier indicating southwesterly flow there. The indicated moisture source is the Gulf of Alaska or possibly the Bering Sea. Another feature of interest on this chart is the extension of the North Pacific High in a ridge through the western Bering Sea into the Chukchi Sea. Comparison with the normal chart (Figure B-7) shows that this ridge has replaced the normal low. This low, the Aleutian Low, has shifted eastwards about 30°. August was used as the normal chart for summer snowfall on Gulkana Glacier instead of July (which was used in the case of summer snowfall on McCall Glacier) as most of the events occurred in this month. The summer period was here defined as 15 May - 15 September. Data from four summers, 1969-1972 were used.

Other features revealed for this case are an eastward extension of the Beaufort Sea High to the Boothia Peninsula and a strengthening of the northeastern extension of the Asian Monsoonal Low (cf. Figure A-2b). This strengthening coupled with the aforementioned strengthening over Alaska allows one to conclude that an increase in cyclonicity north of 60° N in the Alaska region is conducive to snowfall at Gulkana Glacier.

Barter Island

Daily measurements of precipitation during the winter season (~15 September - 15 April) were not made during the McCall Glacier project.

In order to learn what circulation patterns were responsible for significant snowfalls during this period climatic conditions at Barter Island were substituted. In order to test how accurately conditions at Barter Island reflect conditions on McCall Glacier, a MPM and its associated anomaly map were constructed for the case of summer snowfall at Barter Island. The criteria for this case were a precipitation total of 2.5 mm w/e or more in 12 hours and a temperature during the 12 hours of 1.7° C or less. In some of the events the precipitation was liquid, but it was assumed that the precipitation would be solid at least above 1300 m, the lowest elevation on McCall Glacier. The summer season was defined as 15 May - 15 September and data from 9 years, 1964-1972, were used. Although the summer season defined here differs from that defined for McCall Glacier (15 June - 15 August; see Figure A-1a), the MPM's for early fall (15 August - 15 September; Figure A-4a) and spring (15 April - 15 June; Figure A-11a) snowfalls on McCall Glacier are similar enough in form to the MPM for summer to allow one to conclude that an MPM for summer snowfall on McCall Glacier when summer was defined as 15 May - 15 September would not differ substantially than the MPM already obtained.

Figure A-3a is the MPM (# 3) obtained for the condition of summer snowfall at Barter Island. The similarity to MPM # 1 (summer snowfall at McCall Glacier; Figure A-1a) is quite strong. A 1005 mb low is to the ESE, centered near Great Bear Lake. The normal weak high in the Beaufort Sea is missing, but there is a weak high in the East Siberian Sea. The mean geostophic wind at Barter Island is almost directly due north.

MPM # 3 differs from MPM # 1 in that the high in the East Siberian

Sea is not as strongly connected by a ridge to the North Pacific High. Instead, the low pressure trough extending to the west from the Great Bear Lake Low is joined to a trough of low pressure along the 65th parallel in Siberia. The form of this latter trough is similar to that found on the normal chart (Figure B-6), but the overall pressure is higher. The principal difference between MPM # 3 and the normal chart though, is the large negative anomaly east of 170° W longitude (cf. Figure A-3b). The center of this anomaly coincides with the Great Bear Lake Low of the MPM.

Summary

Although there are important differences between MPM's # 1,2, and 3, the similarities are quite pronounced. Increased cyclonicity in the general Alaska - Yukon Territory area was noted for all three MPM's. Also, the weak Beaufort Sea High was destroyed in all three cases while an intensification of the normally weak anticyclone zone in the East Siberian Sea occurred. Since there existed partial overlap in the periods from which the data for these three maps were obtained it might be argued that the similarities that resulted were a result of the same date being an event date for two or more localities. The actual duplication that occurred though, was not great. For example, MPM # 2 had two events that were duplicated on MPM # 1, as well as two that were 12 hours 'off' and one that was 24 hours off. Since there were 23 events for MPM # 1 and 27 for MPM # 2, a total of 5 coincident events does not seem particularly important.

On the other hand, the little duplication that did occur between

MPM's # 1 and 3 was of particular significance. Only four out of 34 snowfall events at Barter Island making up MPM # 3 occurred between 15 June and 15 August, 1969-1972 (the period of 'record' for MPM # 1). Of these four, two were coincident with events on McCall Glacier. Snow fell on the glacier coincident with the other two events, but not enough fell to constitute an event. Thus the similarities revealed between MPM's # 1 and 3 were essentially independently obtained. This fact lends substantial credence to the use of Barter Island as an index station for McCall Glacier.

3.3.2 Fall snowfall

The accumulation season (15 September - 15 June) was arbitrarily divided into fall, winter, and spring seasons. This was done to facilitate comparison of the MPM's with normal charts, charts which change considerably during the year. A fall season defined as 15 September - 15 November was used for all localities except McCall Glacier, where an early fall of 15 August - 15 September was used.

McCall Glacier

MPM # 4 (Figure A-4a) shows the synoptic pattern for the condition of early fall snowfall on McCall Glacier. Data from three years, 1969-1971 were used. This map was quite similar to MPM # 2 (summer snowfall on Gulkana Glacier) with an elongated trough extending from southern Alaska in a northeasterly direction through Alaska and the Yukon Territory. The northeastern portion of the trough is deeper than it was in the Gulkana case though, with a 1000 mb closed low centered just south of Cape Bathurst. The air flow at McCall Glacier is NNW. The low center near Cape Bathurst has weak troughs extending to the southeast and to the north; the latter joins an easterly extension of a low in the Eastern Arctic Ocean. There is a weak high in Eastern Siberia with its center just south of the New Siberian Islands. Comparison with the normal chart (Figure B-8) and the anomaly map (Figure A-4b) shows that the normal elongated Arctic Ocean High has shortened to one center; the Beaufort Sea center is missing entirely. The normal Aleutian Low has been shifted east $20^{\circ} - 30^{\circ}$ over mainland Alaska and the long axis has been rotated from WSW-ENE to SW-NE. Additionally, the Aleutian Low has intensified with the negative anomaly significant at the 95 % confidence level for most of Alaska east of 160° W longitude.

Barter Island

Figure A-5a is the MPM (# 5) for the condition of fall snowfall at Barter Island. Data from five years, 1967-1971, were used. The principal feature of this map is the elongated 1002 mb low extending from Bristol Bay to Kodiak Island. A trough extends to the northeast from the Kodiak center while another extends to the west from the Bristol Bay center. The only high shown is elongated SW-NE from a 1022 mb center near 70° N, 210° W. A weak ridge extends from this high in an arc to Boothia Peninsula. Wind flow at Barter Island is ENE. Since the Beaufort Sea is generally ice free until well into October (NOAA, 1971b), a ready source of moisture is provided. Comparison with the normal chart for October (Figure B-9) and the associated anomaly map (Figure A-5b) reveals that the isobars have been tilted from the normal W-E orientation to a SW-NE orientation. From Figure A-5b it is seen that the most significant anomaly was the positive one in the Eastern Arctic Ocean. Although a closed low to the east or southeast of Barter Island (as in MPM # 3) does not show up on this MPM the largest negative anomaly does appear in this region.

Gulkana Glacier

The situation for fall snowfall at Gulkana Glacier is revealed in MPM # 6 (Figure A-6a). The same definition for the fall season and the same years as used for MPM # 5 were used here. The circulation patterns revealed here are similar to those of MPM # 5 with the features in general more 'normal' (see the anomaly map, Figure A-6b). The orientation of the isobars indicate a SSE flow at Gulkana Glacier. The trough to the northeast of the 1002 mb low centered near Iliamna Lake is a manifestation of a general southwesterly flow aloft. It would appear that this is significant with respect to moisture flux over or around the coastal ranges. The principal features revealed by the anomaly map is the rotation of the long axis of the Aleutian Low from W-E to WSW-NE. The low on the MPM is slightly northwest of the normal position.

Wolverine Glacier

The position of the Aleutian Low for the case of fall snowfall at Wolverine Glacier (MPM # 7, Figure A-7a) is identical to the normal position (cf. Figure B-9). However, the anomaly map (Figure A-7b) reveals that it is much more intense on the MPM than on the normal chart. Also, the long axis of the Aleutian Low on the MPM is N-S while in the normal case it is W-E. A strong anticyclone in Canada exists in the mean case also. This is revealed by the northward extension of this high shown on the MPM and also by the large positive anomaly east of 135° W longitude. The mean geostrophic wind at Wolverine Glacier is from the southeast at $\sim$10 ms^{-1}. The local topography of the Kenai Mountains causes the geostrophic wind to back, so that on the glacier ENE winds would result from a mean flow such as that shown on MPM # 7. Snowdrift patterns in this region indicate that the most vigorous flow is from the ENE.

Summary

A comparison of MPM's # 6 and 7 reveals that the principal difference is one of intensity. Also, the orientation of the trough is different, being more directly N-S in the case of MPM # 7. A minor difference is the more northerly location of the Taimyr Peninsula Trough in the case of MPM # 7. It is not immediately apparent why the circulation pattern shown on MPM # 7 does not also bring heavy snowfall to Gulkana Glacier. Due to the orientation and location of the mountain ranges, though, the exact wind direction at all levels can be crucial with respect to precipitation amounts inland. It is felt that the differences in implied wind trajectories aloft between MPM's # 6 and 7 account for the lack of significant snowfalls at Gulkana Glacier simultaneously with those at Wolverine Glacier.

3.3.3 Winter snowfalls

For all three glaciers the winter part of the accumulation season was defined as 15 November - 15 March. Case normals for winter snowfalls were the same for all three glaciers also; they were composite normals composed of the December and February normals. Data from five winters, 1967/68 through 1971/72, were used for all localities.

Barter Island

MPM # 8 (Figure A-8a) shows the synoptic pattern for the condition of winter snowfall at Barter Island. The dominant feature on this map is the Aleutian Low and the anomalous orientation of its long axis (see the normal map, Figure B-11 and the anomaly map, Figure A-8b). The Arctic Ocean High is well defined with ridges to a northeast cell of the Siberian High and to a high in Northern Canada. An interesting feature of this map is the secondary low pressure cell near Barter Island. The existence of this low and the resultant convergence in the area is probably more significant in this case than the actual mean wind which is weak and ill-defined. On the anomaly map, the dominant feature is the positive anomaly in the Gulf of Alaska. On the normal map this area is covered by an eastward extension of the Aleutian Low but on the MPM it is covered by a ridge extending from the North Pacific High. The inference is that this high acted as a blocking high, steering cyclones around Alaska. Simultaneously, the ridge of high pressure that normally extends in an arc across the Arctic Ocean south of the 80th parallel has been shifted about 8° north. The implied storm track here suggests that the Pacific Ocean was the primary source of moisture. The negative anomaly area centered just to the northeast of Barter Island reflects the fact that snow fell in the mean after the secondary low had passed Barter Island. The occurrence of cold type occlusions no doubt contributed to this phenomenon.

Gulkana Glacier

MPM # 9 (Figure A-9a) reflects the situation for winter snowfall at

Gulkana Glacier. A slight but significant departure from the normal distribution of pressure occurred for this MPM (cf. Figure B-11). The Aleutian Low is well defined with a 996 mb center located near 50° N, 185° W. From this center the normal eastward trough is extended in an arc to the northeast, with the axis of the trough lying near Gulkana Glacier. This configuration indicates a SSE flow at Gulkana Glacier with an implied trajectory from the southwest. Such a trajectory allows an influx of moisture to the north and northwest of the coastal ranges similar to that implied by MPM # 6, the case of fall snowfall. The normal ridge of high pressure extending from Siberia to Northern Canada has been shifted northwards in the central Arctic Ocean. The anomaly areas shown in Figure A-9b reflect the tilting of the eastward trough of the Aleutian Low. Thus the Eastern Gulf of Alaska is an area of positive anomaly while Northern Alaska is an area of negative anomaly. The positive anomaly in the Eastern Gulf of Alaska could also be interpreted as the westernmost extension of a blocking high, causing cyclones to take a more northerly track.

Wolverine Glacier

MPM # 10 (Figure A-10a) shows the synoptic pattern for the condition of winter snowfall at Wolverine Glacier. The mean low shown here is similar in location and intensity to that found in the case of fall snowfall (MPM # 7). In the present case the central pressure is approximately 986 mb and the trough has a WSW-ENE tilt. The resultant flow at Wolverine Glacier is from the ESE with a speed of $\sim 10\ ms^{-1}$. When compared to the normal chart (Figure B-11) it is seen that the Aleutian Low is is much more intense and that the two centers have been merged into one and shifted eastwards. The slight tilt of the trough's axis results in a slightly amplified arc in the ridge coccecting the Siberian and Canadian Highs. Inspection of the anomaly map (Figure A-10b) reveals a large negative anomaly area centered near Cold Bay, Alaska, the location also of the MPM low.

<u>Summary</u>

Although virtually all of Alaska has negative pressure anomalies significant at the 95 % confidence level, the individual circulation patterns that make up MPM # 10 (winter snowfall at Wolverine Glacier) do not cause uniformly heavy snowfall at Gulkana Glacier even though the indicated wind is from the south. The key to this apparent paradox is similar to that found in the case of fall snowfall. The trajectory of the air and thus the moisture source differs significantly between MPM's # 9 and 10. Thus in the former, moisture can reach Gulkana Glacier by skirting the coastal ranges while in the latter these ranges offer direct obstacles to the flow, drying it out before it can reach the Alaska Range and Gulkana Glacier.

3.3.4 Spring snowfall

The third part of the accumulation season, spring, was defined differently for the several locations. For McCall Glacier the period 15 April - 15 June was used. For Gulkana and Wolverine Glaciers, it was defined as 15 March - 15 May. Finally, to cover the period 15 March - 15 April and to provide further comparison with the Gulkana and Wolverine Glaciers, a spring season of 15 March - 15 June was defined for McCall's index station, Barter Island.

McCall Glacier

MPM # 11 (Figure A-11a) shows the synoptic pattern for the condition of spring snowfall at McCall Glacier. Data from three springs, 1970-1972, were used. As in the cases for summer and fall snowfall a mean low is found to the east of McCall Glacier. In the present case it is centered near Great Bear Lake. A weak trough extends in an arc from this low across Central Alaska to Bristol Bay. The western center of the Aleutian Low is found just southeast of the Kamchatka Peninsula. The Arctic High is located near 85° N, 145° W with a ridge extending southwards to the Bering Sea. The resultant wind at McCall Glacier again has a northerly component indicating a recent Arctic Ocean trajectory (see discussion in Section 3.3.1). Comparison with the normal map (Figure B-3) shows that the Aleutian Low has been split into two with each center intensified. Concurrently, the Arctic High has shifted northwards about 8°. Comparison with the anomaly map (Figure A-11b) shows that the largest anomalies are the negative ones associated with the two split branches of the Aleutian Low. The center of the eastern negative anomaly is situated north of the MPM low. This position is closer to that occupied by the mean lows in the cases of summer and fall snowfall at McCall Glacier (MPM's # 1 and 4).

Barter Island

When the situation of spring snowfall at Barter Island is investigated the result is gratifyingly similar to that found for McCall Glacier. The MPM (# 12) for this situation is given as Figure A-12a. Data from five years, 1968-1972, were used. The Aleutian Low has been split into two centers, as in the case of MPM # 11, but they are rather large and diffuse. Also, the Arctic High is longer and is connected by a ridge to the North Pacific High. The resultant wind at Barter Island (and at McCall Glacier), though, is almost directly from the north. Inspection of the normal map (Figure B-2) and the anomaly map (Figure A-12b) reveal much the same pattern as found in the case of MPM # 11. The anomaly patterns and the 95 % confidence level areas are somewhat different in detail, though. The positive anomaly found between the split MPM low has an area significant at the 95 % confidence level in the present case. In the former, the significant anomaly coincides with the western center of the Aleutian Low. Also, in the present case, the eastern negative anomaly area is shifted to the north with the center almost due northeast of Barter Island.

Gulkana Glacier

The MPM for the condition of spring snowfall at Gulkana Glacier (MPM # 13, Figure A-13a) was composed of data taken from five years, 1968-1972. This map is dominated by a low which covers all of Alaska and considerable surrounding area. A weak trough extends in an arc to the east from the 1000 mb center near McGrath, Alaska. Another arc extends to the southwest. The pattern of the anticyclones with centers in Siberia near 65° N, 215° W and in the Arctic Ocean near 80° N, 115° W, and their connecting ridges contributes to the marked SW-NE orientation of the isobars. The resultant wind at Gulkana Glacier is almost directly due south. As in the case of McCall Glacier and Barter Island the pattern for Gulkana Glacier is remarkably similar throughout the accumulation season. Comparison with the normal map (Figure B-1) shows cyclonicity has increased in Alaska in the MPM case at the expense of anticyclonicity. The Aleutian Low, which has two centers in the normal case, has merged into one center and intensified. This center has shifted northeast of the normal position and the long W-E axis has been tilted to the northeast. Concurrently, the Arctic High has decreased in area and the ridges connecting it to the Siberian and Canadian Highs have shifted northwards. The anomaly map (Figure A-13b) reveals a large negative anomaly centered near the mean low in southwestern Alaska. The tilting of the Aleutian Trough is further revealed by the appearance of two positive anomaly areas, one in the far Eastern North Pacific Ocean and one centered in the Northern Okhotsk Sea.

Wolverine Glacier

The last MPM for accumulation season snowfall, MPM # 14, is for the condition of snowfall at Wolverine Glacier (Figure A-14a). As in the case of fall and winter snowfall at Wolverine Glacier, the MPM is dominated by an intense low. In this case it is centered in Bristol Bay with a central pressure estimated at 986 mb. The resultant wind at Wolverine Glacier is SSE. Comparison with the normal map (Figure B-1) shows that the principal change has been an intensification and northwestward shift of the eastern center of the Aleutian Low at the expense of the western center. Little change has occurred in the position of the Arctic High and its associated ridges. As a result pressure gradients, especially over Alaska have increased. Figure A-14b, the anomaly map, exemplifies this very dramatically, with a very large negative anomaly depicted. The area significant at the 95 % confidence level covers all of Alaska west of 150° W longitude, extending southward to 50° N and west to 180° longitude.

Summary

On MPM # 13 (spring snowfall on Gulkana Glacier) the Brooks Range is covered by a negative anomaly that is significant at the 95 % confidence level. However, this MPM is not a pattern conducive to substantial snowfall there, particularly in the northern sections. The position of the mean low and its associated trough indicate that most of the potential moisture probably was released over the Alaska Range.

3.3.5 Hot spells

Hot spells occurred at the three glaciers almost uniformly in the months of June and July. By August large scale circulation changes generally bring cloudier and more cyclonic weather to all of Alaska. Additionally, by then there is a reduction of solar radiation which is especially significant in these northern latitudes.

McCall Glacier

MPM # 15 (Figure A-15a) shows the synoptic pattern for the condition of hot spells at McCall Glacier. Data from four summers, 1969-1972, were used. The proximity of the high to the east and the resultant air flow indicate clear skies at McCall Glacier. The resultant geostrophic wind is ESE so there is no flow over water. The isobars in MPM # 15 are straight near McCall Glacier and inspection of the individual events comprising this case (see discussion Section 4.2) revealed an even distribution of events with anticyclonic and cyclonic curvatures. However, even in those events that had cyclonic curvature mechanical subsistence probably occurred. Considering implied trajectories, it is seen that the air over McCall Glacier in MPM # 15 had a long overland path with the final portion of the trajectory over the Eastern Brooks Range. Altogether, these conditions strongly suggest clear skies at McCall Glacier, thus allowing strong radiational heating and warm temperatures. Actual on-glacier observations confirmed clear skies in a majority of events. The presence of the mean low in the Central Bering Sea is anomalous as inspection of the normal chart (Figure B-4) and the anomaly map (Figure A-15b) reveals. Also of interest is the strong high cell in the Laptev Sea. A further feature of interest is the intensified heat low in Interior Alaska. It is concluded that when the planetary circulation pattern is such that a strong Aleutian Low is coupled with a strong high in the Laptev Sea the regional circulation in Alaska will favor hot spells at McCall Glacier. Also of importance is the positive anomaly in North Central Canada. This indicates that the high centered near Western Victoria Island is stronger than normal. This increase in strength might be crucial in insuring at least 'straight isobar flow' at McCall Glacier.

Gulkana Glacier

MPM # 16 (Figure A-16a) shows the synoptic pattern for the condition of hot spells at Gulkana Glacier. Data from five summers, 1968-1972, were used. This map is marked by an anomalous tilt and intensification of the Aleutian Low (cf. Figure A-16b) and a compensatory buildup of the Arctic High. The position of this high in the Beaufort Sea is normal but the increase in its strength is anomalously high at the 95% confidence level for all of Alaska north of the coastal ranges plus the Beaufort Sea. At Gulkana Glacier the indicated geostrophic wind is virtually calm but the anticyclonic circulation insures that clear skies and radiational heating were present. At McCall Glacier, though, the indicated air flow indicates a trajectory over the Beaufort Sea and thus the possibility of increased cloudiness and fogginess. This fact probably explains why the circulation pattern shown in this MPM is not bad for McCall Glacier.

Wolverine Glacier

MPM # 17 (Figure A-17a) reveals the situation for hot spells at Wolverine Glacier. Data from six summers, 1967-1972, were used. The circulation pattern shown here is quite different from those found for McCall and Gulkana Glaciers. Basically, the Pacific Subtropical High has been pinched northwards, joining the Arctic High which has been displaced southwards into northwestern Canada. The Aleutian Low does not appear in this MPM; there is only a weak trough extending in an arc eastwards and southwards from the northward extension of the Asian Monsoonal Low in the Western North Pacific just east of Kamchatka Peninsula. The alighment of the mean isobars indicate strong blocking; the only cyclonicity indicated east of 180° longitude is a weak low off the tip of Southeast Alaska. The implied wind direction at Wolverine Glacier is probably preferred for clear weather as it is essentially over land. This direction of the wind coupled with the anticyclonic circulation make the occurrence of strong radiational heating and warm temperatures easy to understand. An additional contribution is the light pressure gradient.

The lack of any mean pressure gradient over most of Alaska make it difficult to explain why this MPM does not also represent bad circulations for McCall and Gulkana Glaciers. At McCall, the same mechanism that seemed apparent in MPM # 16 might be operating, namely onshore flow. The situation at Gulkana Glacier though, does not allow even this much of an excuse. Thus, hot spells at all three glaciers were climatic conditions for which the basic MPM analysis was extended (cf. Chapter 4).

3.3.6 Summary

When the several MPM's for each glacier that represent snowfall events are compared, several interesting similarities and differences are revealed. In the cases for Wolverine Glacier (MPM's # 7, 10, and 14) the Aleutian Low is strongly intensified with an average location of 57° N, 160° W, about 750 km southwest of the glacier. There is no strongly marked trough toward the northeast. In the cases for Gulkana Glacier, the Aleutian Low is intensified but not as strongly as in the Wolverine Glacier cases. The average position is 61° N, 155° W, about 550 km southwest of Gulkana Glacier. A well defined trough exists to the northeast with its axis lying near the Alaska Range and Gulkana Glacier. The cases for McCall Glacier and Barter Island are more variable. However, most of the maps for accumulation season snowfall there (MPM's # 4, 5, 8, 11, and 12) show a low or a well developed trough in the general region to the east and southeast. The average position for these lows and troughs is $67\frac{1}{2}$° N, 130°W, about 600 km southeast of McCall Glacier.

One common pattern in all three of the MPM's for hot spells is the existence of anticyclonic circulation near the glacier in question. In the cases for Gulkana and Wolverine Glaciers a strong positive pressure anomaly centered near the glacier existed, while in the case of McCall Glacier a compensating negative pressure anomaly area to the southwest existed.

CHAPTER 4

EXTENSION OF THE BASIC MPM APPROACH

4.1 Introduction

There are several questions in the topic of glacier/climatic relationships in Alaska which can be answered more fully by extending the basic MPM approach. For example, the MPM for summer snowfall at McCall Glacier (MPM # 1, Figure A-1a) shows a 1006 mb low east of the glacier and a general area of low pressure in the Canadian Arctic Islands and the Eastern Arctic Ocean. With respect to causes of glaciation, Benson (1967) has suggested "... that the Canadian Arctic Islands and the Arctic Coast in the Alaskan-Yukon border region constitute a critical area of unstable equilibrium". Thus, an investigation into the events comprising MPM # 1 and their history would aid in explaining the processes operating in this critical area.

In the discussion of the MPM's in Chapter 3 several examples were given where ambiguities existed between MPM's for different glaciers for the same type of condition. Thus, why was not MPM # 17, the MPM for hot spells at Wolverine Glacier, a bad event for Gulkana Glacier? In situations such as this an investigation of the individual maps can reveal subtle differences that perhaps can answer this.

Another question unanswered by the basic MPM approach is that of representativeness. Is the MPM representative of the individual maps comprising it?

An investigation into each event of each MPM was clearly not possible, however. Because of the critical nature of summer snowfall (see discussion in Section 3.3.1) MPM's # 1 and 2 (summer snowfall on McCall and Gulkana Glaciers respectively) were selected for extending. Hot spells are also critical as they were the only bad events studied. Therefore, MPM's # 15, 16, and 17 were also selected for extending.

4.2 Representativeness of MPM's

4.2.1 Introduction

The representativeness of the MPM's was tested in two ways. The first method was subjective; each event map of a particular MPM was visually inspected as to whether or not it was similar to the MPM. In doing this it was found useful to 'type' the event maps. Typing was done independently between MPM's. That is, for example, the event maps for hot spells at McCall Glacier (MPM # 15) were all typed first, then those for Gulkana Glacier were typed, and finally those for Wolverine Glacier were typed. Another approach would have been to type all the event maps without regard to the MPM they each belonged to. The different patterns revealed by the different types serve to extend the MPM; however, the primary reason for typing was to assist the testing of MPM representativeness. The second method was objective; standard deviations of pressure at each grid point for a particular MPM were calculated and compared to the 'true' standard deviation of pressure for the appropriate period. This method was applied to MPM's # 1,2, and 16.

4.2.2 Summer snowfall events

<u>McCall Glacier</u>

The MPM for summer snowfall on McCall Glacier (MPM # 1, Figure A-1a) consisted of 23 individual events. The typing procedure revealed seven different varieties. Of these seven varieties two had seven events each, two had three each, and three had one each. Figure D-1 is a typical MS1 event. For this type there is a strong low in the Arctic Ocean north of 75° N latitude. The geostrophic flow at McCall Glacier was from the northwest quadrant. All seven of these events were chosen similar to the MPM. Although a closed low near 70° N, 130° W did not exist for some of the MS1 events, the low in the Arctic Ocean was considered important and 'similar' to the low pressure area shown on the MPM. Figure D-2 is a typical MS2 event. Three events were of this type. It is distinguished by a weak low over or just to the north of the North Slope of Alaska. The flow at McCall Glacier was WSW to WNW. One of these events was deemed similar to the MPM while the other two were judged dissimilar. Figure D-3 is a typical MS3 event. A dominant low is east or northeast of McCall Glacier. The resultant wind flow there was from the northwest quadrant. All seven of the MS3 events were judged similar to the MPM. Three events were MS4 type events (Figure D-4) and all were judged similar to the MPM. In this type there is a weak low southeast of McCall Glacier near Great Bear Lake. The resultant flow at the glacier is weak, from a north to northeast direction. The remaining three types, MS5, MS6, and MS7 were all judged dissimilar to the MPM. Altogether, 18 out of a total of 23 events were judged similar to MPM # 1.

Standard deviations of daily pressure for each grid point, true standard deviations, were calculated based on the 25-year series of monthly mean charts and values of the one-day lag autocorrelation coefficient (see Section 3.2.3). Another set of standard deviation, 'MPM standard deviations', can be obtained using the pressure values from the events making up an MPM. If the MPM is representative of the individual events the MPM standard deviations should be less than the true standard deviations, after due consideration is taken of the number of events making up the MPM. According to Brooks and Carruthers (1953, p. 58) the standard error of the standard deviation in a nearly normal distribution is given by $(\sigma^2/N/2)^{\frac{1}{2}}$. This means that 67 % of the time the MPM standard deviation, σ_x, will fall in the interval $\left[\sigma(1+\sqrt{2/N})^{-1}, \sigma(1-\sqrt{2/N})^{-1}\right]$, where σ is the true standard deviation and N is the number of events in MPM # x. It is to be expected that there would be grid points where σ_x is not contained in the above interval. In fact, since pressure at one grid point is not independent of the pressure at surrounding grid points it is to be expected that there would be regions where σ_x was either above or below the given interval. Figure 4-1 is a map of the Alaska region showing those areas where σ_1 was either above or below the given interval. In general, areas where $\sigma_1 > \sigma(1-\sqrt{2/N})^{-1}$ * imply a higher than usual rate of alternation of cyclones and anticyclones while areas where $\sigma_1 < \sigma(1+\sqrt{2/N})^{-1}$ imply the opposite. It is interesting to note the small area near Great Bear Lake where σ_1 was significantly less than σ. The pressure in this area varied less from one map to another of those making up the MPM than would be expected in a purely random situation, and it can thus be concluded that cyclones were dominant in this region in a statistical sense. This conclusion is substantiated by the results of the investigation of the individual maps making up the MPM reported above.

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* N = 23 for MPM # 1.

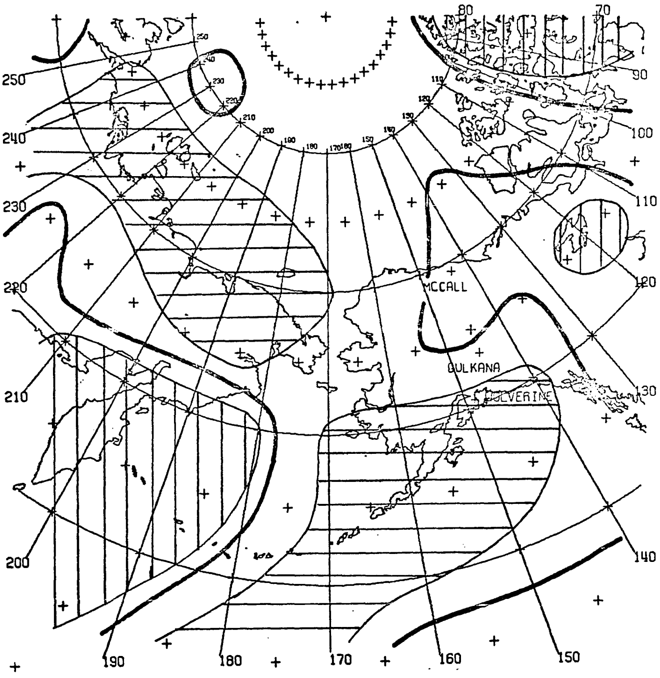

Figure 4-1. Representativeness of MPM # 1. Areas where $\sigma_1 < \sigma(1 + \sqrt{2/N})^{-1}$ have vertical hatching; areas where $\sigma_1 > \sigma(1 - \sqrt{2/N})^{-1}$ have horizontal hatching. Solid line is isoline for $\sigma_1 = \sigma$.

Gulkana Glacier

The MPM for summer snowfall on Gulkana Glacier (MPM # 2, Figure A-2a) consisted of 27 individual events. These 27 events were typed into seven different varieties. There were 11 GS1 type events, 5 GS2 type events, one GS5 type event, and two each events for the remaining four types. Figure D-5 is a typical GS1 event. This type was distinguished by a trough of low pressure extending in a general W-E direction across Alaska. There was considerable variation within this type, usually with regard to the exact location of the low, if one existed. A trough always existed with an axis lying to the north of Gulkana Glacier. Thus, the resultant flow at the glacier was from the south. Ten of the eleven events of this type were similar to the MPM. Figure D-6 is a typical GS2 event. This event was marked by two low pressure systems; one was to the north or northeast of Gulkana Glacier while the other was to the southwest in the Bering Sea. Sometimes this second low was missing, but then a general N-S trough extended from the first low. Only two of these events were judged similar to the MPM. Figure D-7 is one of the three events judged dissimilar. In the remaining five types there were a total of five events judged similar to the MPM and four judged dissimilar. Altogether 18 individual events were judged similar to the MPM and 9 dissimilar.

Another, coarser typification was made based on the geostrophic wind direction at Gulkana Glacier. There were 22 examples with a southerly flow and 5 with a northerly flow. Fourteen of the former were similar and four dissimilar to the MPM. Also, in 26 of the 27 events low pressure systems dominated the area near Gulkana Glacier. When the one spurious anticyclonic case was thrown out the resulting MPM (Figure 4-2) was slightly more definitive than the original MPM (Figure A-2a). When the two MPM's are compared it is seen that the area in the Central Alaska - Yukon Territory region enclosed by the 1006 mb isobar is larger in the new MPM, MPM # 2'. Otherwise, the pattern is almost identical.

MPM standard deviations were also calculated and compared to the true standard deviations for this case. The same sort of analysis used in the McCall Glacier case was used in the Gulkana Glacier case. Figure 4-3 then, is analogous to Figure 4-1. The results here were not as conclusive though, as comparison of the two maps shows. Analysis of the individual maps making up MPM # 2' (this MPM was used rather than MPM # 2 for the standard deviation analysis) revealed more diverse types than found in the case of MPM #1. Another explanation for the apparent lack of representativeness revealed by the standard deviation analysis can be obtained by considereing the two standard deviations used to construct the map in Figure 4-3 and their respective populations. The true standard deviation has a population that includes anticyclonic events as well as cyclonic events. The former tend to be more persistent than the latter so that the resultant standard deviation is smaller. The MPM standard deviation, on the other hand, has a population that is exclusively made up of cyclonic events. Thus, nonrepresentativeness is not necessarily implied in this case even if the MPM standard deviations are greater than the true standard deviations. Finally, it should be noted that the true standard deviations are partially based on relatively poor pre-1950 data (see Section 3.2.3).

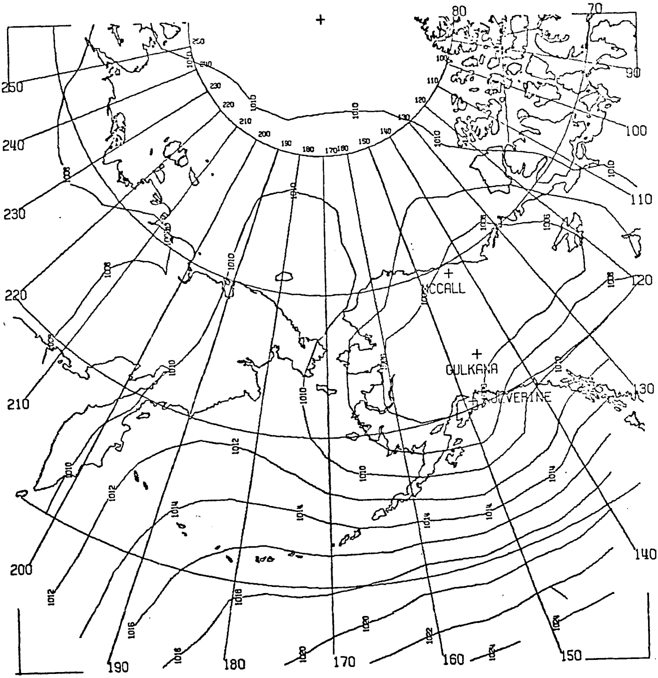

Figure 4-2. MPM #2'. Mean pressure for 26 summer snowfalls (>7mm w/e $12h^{-1}$), 1969-1972, Gulkana Glacier.

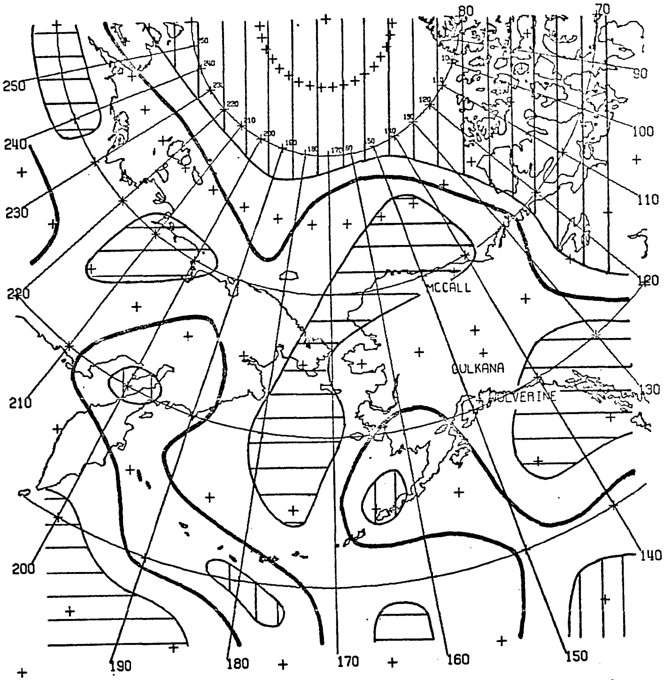

Figure 4-3. Representativeness of MPM # 2. Areas where $\sigma_2 < \sigma(1 + \sqrt{2/N})^{-1}$ have vertical hatching; areas where $\sigma_2 > \sigma(1 - \sqrt{2/N})^{-1}$ have horizontal hatching. Solid line is isoline for $\sigma_2 = \sigma$.

Summary

Analysis of the individual maps making up MPM's for summer snowfall events has revealed that the MPM's are representative. Thus, 78 % of the events making up the MPM for summer snowfall at McCall Glacier were judged similar to the MPM, while 69 % of those in the Gulkana Glacier case were judged similar to the MPM. There were no significant differences in average snowfall amounts between the representative and nonrepresentative events for either glacier.

When the process of typing is considered as an extension of the MPM approach the possibility of a systematic variation in snowfall amount between different types is raised. The events comprising MPM's # 1 and 2 were therefore grouped according to type and the average snowfall amounts for each type compared. For the McCall Glacier case (MPM # 1) no systematic variation was found; average snowfall amounts were grouped in the small range of 4.5 to 5.5 mm w/e. In the Gulkana Glacier case (MPM # 2) though, a possible systematic variation was revealed. The average snowfall amount for the 27 events comprising this case was 13.3 mm w/e; for type GS1 the average was 10.7 mm w/e, and for type GS2 (the only other type that had more than two events) it was 21.8 mm w/e. However, this latter type only had five events, in one of which 32 mm w/e of snow fell. Although the results are interesting and suggestive of further insights into the important dynamics responsible for snowfall on Gulkana Glacier, more events would be necessary before the existence of a systematic variation in snowfall amounts by type could be established with any certainty.

The use of MPM standard deviations to test representativeness were not as powerful a tool in the case of summer snowfall events. Figures 4-1 and 4-3 though, are interesting maps and serve as further aids in analyzing and understanding the MPM's. Topologically, they seem similar to Reed and Kunkel's "Rate of alternation between cyclones and anticyclones" map (Reed and Kunkel, 1960, Figure 5, p. 494).

4.2.3 Hot Spells

The individual maps making up the MPM's for hot spells included some maps for 0200 LT (1200 GMT). This was done when two or more consecutive days qualified as hot days on a particular glacier. However, when the basic MPM analysis was extended and the representativeness of the MPM's was studied, only the 1400 LT (0000 GMT) maps were investigated.

The MPM's for hot spells at the three glaciers were similar to the extent that the ~30 events making up each MPM were composed of ~10 hot spells; periods of two or more days when particular synoptic patterns persisted. For this reason it was felt that a standard deviation test of representativeness for only one glacier would be sufficient. Gulkana Glacier was selected for this test.

McCall Glacier

There were 19 1400 LT (0000 GMT) maps included in the 28 maps making up MPM # 15 (Figure A-15a), the MPM for hot spells at McCall Glacier. These 19 individual events were classified into three types. Figure D-8 is a typical MH1 event. There were two basic criteria for this type: a high in the Beaufort Sea and a low in the Gulf of Alaska. The geostrophic wind at McCall Glacier varied from southeast to east. All five of the MH1 events were judged similar to the MPM. Figure D-9 is a typical

MH2 event. Essentially, this was the reverse of MH1 with a low in the Arctic Ocean and a high in the Gulf of Alaska. All of these events were judged dissimilar to the MPM. The flow at McCall Glacier varied within this type; in three events it was anticyclonic flow from the Gulf of Alaska High while in one event (Figure D-10) it was cyclonic flow from the Arctic Ocean Low. In this last event the 0200 LT (1200 GMT) map, as well as the previous day's 1400 LT map would have been more representative of the synoptic situation giving rise to the high mean daily temperature. The synoptic pattern revealed in Figure D-10 is more typical of those discussed above with respect to snowfall events. Actually, the weather on McCall Glacier changed on June 19th from a hot spell regime to a stormy snowfall regime. Although the mean daily temperature exceeded the threshold value of 8.5° C, it was falling by 1400 LT and snow occurred on the glacier before 2400 LT.

Figure D-11 is a typical MH3 event. This type was distinguished by a high in the Beaufort Sea or a ridge of high pressure connecting a high in the East Siberian Sea with one in Northern Canada. Also, there was a high in the Gulf of Alaska, while a low was in the Bering Sea. Frequently there was a heat low in Interior Alaska. There were 10 instances of this type, all of which were judged similar to the MPM. Altogether, 15 maps were judged similar (types MH1 and MH3) to the MPM and four dissimilar (type MH2).

Gulkana Glacier

The situation at Gulkana Glacier was not as simple as that of McCall Glacier. Although 17 of the 20 maps studied were judged similar to the

MPM (MPM # 16, Figure A-16a), the breakdown evinced seven types. Only two of these types, GH1 and GH5, had five or more events. Figure D-12 is a typical GH1 event. This type was similar to the MH1 event with a high in the Beaufort Sea and a low in the Gulf of Alaska. There was no low in Interior Alaska. All five of this type were judged similar to the MPM. Also, all of these events occurred before the McCall Glacier Project field work commenced. Therefore, it is not known if these were also bad events for McCall Glacier. Figure D-13 is a typical GH5 event. This event was also similar to a McCall Glacier type, type MH3. There was a high to the north of Gulkana Glacier, frequently in the Beaufort Sea, a high in the Gulf of Alaska, and a low in the Bering Sea or near the Western Aleutians. There was no heat low in Interior Alaska. Four of the five events of this type, including the one shown in Figure D-13, were judged similar to the MPM. Of the remaining five types, three included heat lows in Interior Alaska as part of their defining criteria. There were eight events in these three types. Figure D-14 is an example of a type, GH7, with a heat low in Interior Alaska. Although the MPM does not explicitly show a heat low, the dominant MPM feature of a high in the Beaufort Sea and a trough of low pressure stretching from north central Siberia to the Western Bering Sea are present in Figure D-14. Therefore it was judged similar to the MPM.

Figure 4-4 is a map analagous to those shown in Figures 4-1 and 4-3. It shows the areas where the MPM standard deviation of pressure is significantly larger or smaller than the true standard deviation. In this case, the MPM is that for hot spells at Gulkana Glacier. The two regions, where the MPM standard deviations were significantly less than the

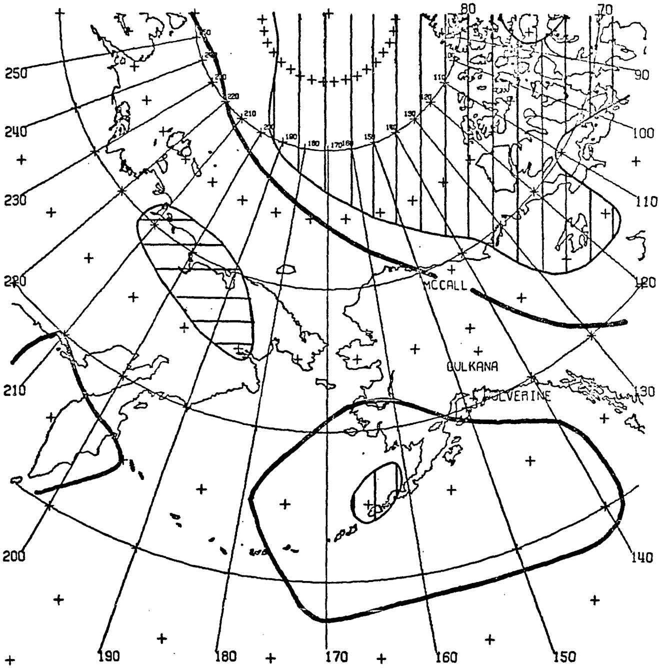

Figure 4-4. Representativeness of MPM # 16. Areas where $\sigma_{16} < \sigma\,(1 + \sqrt{2/N}\,)^{-1}$ have vertical hatching. Areas where $\sigma_{16} > \sigma\,(1 - \sqrt{2/N}\,)^{-1}$ have horizontal hatching. Solid line is isoline for $\sigma_{16} = \sigma$.

true standard deviations, are clearly greater in area than the one region where the opposite obtained. Thus, even though the region immediately adjacent to Gulkana Glacier has MPM standard deviations greater than true standard deviations, the vertically hatched areas to the northeast and southwest in Figure 4-4 indicate an overall reduction of variability among the individual maps comprising the MPM. Therefore, the MPM can be judged representative of the individual maps in a statistical sense.

Wolverine Glacier

The investigation of representativeness of MPM # 17 (Figure A-17a), the MPM for hot spells at Wolverine Glacier, resulted in six basic types being identified. A total of 22 maps were drawn and studied. Figure D-15 is a typical WH1 event. The WH1 type was distinguished by a ridge of high pressure extending to the north from the North Pacific High influencing virtually all of Alaska. A low pressure cell was frequently noted in the Eastern Gulf of Alaska. There were eight instances of this type, all of which were judged similar to the MPM. Figure D-16 is a WH2 type event. It is similar to the WH1 events except that all of Alaska is not influenced by the high ridge extending from the south. In the WH2 type events the northern and sometimes the central part of Alaska was influenced by a low pressure system in the Arctic Ocean. All of the four WH2 events were judged similar to the MPM. Figure D-17 is a typical WH4 event. This type was characterized by two highs, the first being the same as that described for WH1 and WH2 types, while the second was located in the Beaufort Sea. Sometimes the two centers were connected by a ridge of high pressure while at other times a weak heat low in Interior

Alaska separated them. The other three types accounted for six individual events. Altogether 18 of the 22 maps were judged essentially similar to the MPM.

Summary

MPM's for hot spells at the three glaciers were all fairly representative of the individual maps comprising them. In some cases, a particular synoptic pattern was bad for two glaciers, although not a single event was simultaneously bad for all three glaciers. Between McCall and Gulkana Glaciers there were three common events, while between Gulkana and Wolverine Glaciers there were five common events. Interestingly enough, there were two common events between McCall and Wolverine Glaciers.

The curvature of the isobar nearest a particular glacier was not critical. Frequently the pressure gradient was weak so that the implied curvature had little impact. For Wolverine Glacier there were 14 events with anticyclonic curvature and 8 with cyclonic curvature. The situation at Gulkana Glacier was the opposite with only 6 events having anticyclonic curvature while 14 had cyclonic curvature. The presence of a weak low, oftentimes very weak, was responsible for this situation. Finally, at McCall Glacier the individual events were fairly evenly divided with 10 events having anticyclonic curvature and 9 having cyclonic curvature. Curvature of the isobars at a higher level, perhaps 850 mb, might reveal more consistency.

4.3 Event History

4.3.1 Introduction

The history of individual events can be succinctly described by cyclone tracks, where appropriate. These in turn can indicate original and contributary moisture sources. However, the intent here is not so much to delineate sources of moisture and their relative importance (with respect to McCall Glacier, for example) but rather to illustrate the dynamic processes that are operating during the individual events. Thus, the results presented in this Section regarding cyclone tracks, sources of moisture, etc., serve primarily to elucidate the MPM's.

Each month the National Climatic Summary gives cyclone tracks for all of North America (NOAA, 1969-1971). Not shown there are tracks with lifetimes less than 24 hours or tracks which fall west and north of the line drawn slantwise down the center of Figures 4-5a and 4-5b. The storm track analysis reported here was based on the data in this publication. To supplement the storm track analysis a brief discussion of the synoptic patterns and their changes are given for a few events.

It was anticipated that the majority of storm tracks for Gulkana Glacier events would originate in the Pacific Ocean. Initial analysis confirmed this. Therefore, the storm track analyis reported here was confined to McCall Glacier events.

4.3.2 Storm tracks

Figure 4-5a shows the storm tracks for six July events and Figure 4-5b shows the storm tracks for eight August events. The tracks on Figure 4-5a will be referred to as J1 - J6 while those on Figure 4-5b will be referred to as A1 - A8. The open circles show the positions of the cyclones when snow fell on McCall Glacier. Inspection of Figures 4-5a and 4-5b reveal that both the Pacific and Arctic Oceans, as well as interior regions were moisture sources for cyclones that brought snow to

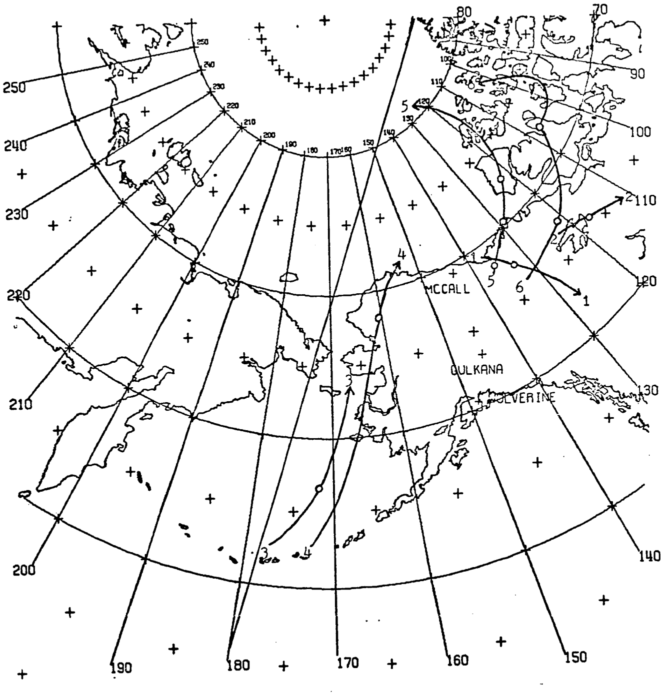

Figure 4-5a. Tracks of July cyclones associated with snowfall on McCall Glacier, 1969-1971.

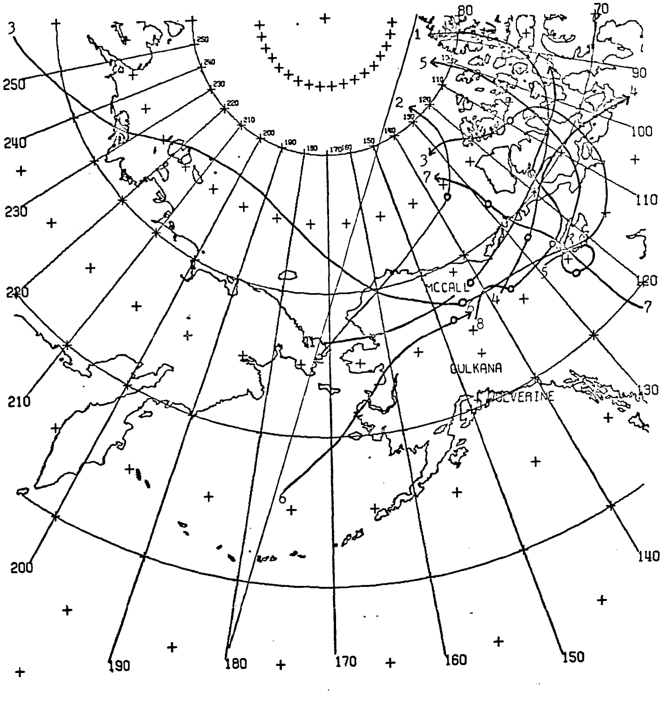

Figure 4-5b. Tracks of August cyclones associated with snowfall on McCall Glacier, 1969-1971.

McCall Glacier. However, even those cyclones that originated along the Arctic Front when it lay in Arctic waters (e.g. track A1) probably had most of their mositure derived from relatively warm Pacific air. The effect of orographic uplift (see discussion in Section 3.3.1) was considerable and no doubt increased the effect of the generally drier Arctic Ocean storms. Furthemore, this effect would also act to increase precipitation amounts from cyclones whose original moisture was derived from Pacific Ocean sources. The mean cyclone track represented by tracks J4 and A2 has been alluded to previously. This track was favored when a blocking high developed over the Gulf of Alaska. In cyclones that took this track, depleted moisture in the northwest quadrant would be partially restored from the Arctic Ocean, especially if the storm stalled upon entering the Arctic Ocean. Even so, the Pacific Ocean moisture would be predominant. Mention is made of this effect, only in so far as the small Arctic Ocean contribution might be critical.

Many cyclones that brought snow to McCall Glacier had a track through the Canadian Archipelago. Tracks A1, A5, J5, and J6 are examples of this track. Klein (1957), in his monumental work on cyclone and anticyclone tracks, does not show such a path for either July or August (his Charts 55 and 56). For August however, he shows an area of cyclogenesis near 63° N, 130° W. From this area of cyclogenesis a primary storm track extends in an ESE direction, crossing Hudson Bay and curving to the north by the west coast of Greenland. On Figures 4-5a and 4-5b however, a general area of cyclogenesis is shown further north, near latitude 66° N. It can be speculated than, that if the area of cyclogenesis found by Klein is shifted north by several degrees of latitude the resultant storm tracks are favorable for snowfall in the Northern Brooks Range.

4.3.3 Representative cases

10-12 August 1969

Cyclone track A3 is an example of a 'pure' Arctic Ocean Cyclone and, because of this the track depicted by NCAA (1969-1972) was extended backwards. The National Meteorological Center's series of surface analysis maps for the North Pacific Region were used for this operation. On these maps, this cyclone was first noted on 5 August at 0600 GMT, near 65° N, 260° W. It was then associated with a warm type occlusion. Moving in a general northeasterly direction the cyclone deepened and moved offshore near 235° W between 0600 and 1200 GMT on 7 August. By 1200 GMT on the 8th the cyclone was located near 77° N, 197° W and had been transformed into a cold type occlusion. It then curved toward the southeast, accelerated and deepened; it moved onshore mainland Alaska near Wainwright, about 150 km southwest of Barrow around 0600 GMT on the 9th. At that time the central pressure was ~998 mb. At 0000 GMT on the 10th the center was near 67° N, 145° W and the central pressure had further dropped to 992 mb (Figure 4-6). Strong winds and light snow was observed at McCall Glacier. However, not enough snow fell in the 12 hour periods ending at 0600 and 1800 GMT on the 10th for either period to qualify as a snowfall event. Interestingly enough, enough snow did fall on Gulkana Glacier in the 12 hour period ending at 1800 GMT for that period to qualify as an event for that glacier. Moving eastward the cyclone filled and weakened. Meanwhile a 500 mb low located ~1000 km north of Alaska began drifting to the southeast. The surface low next began curving northward

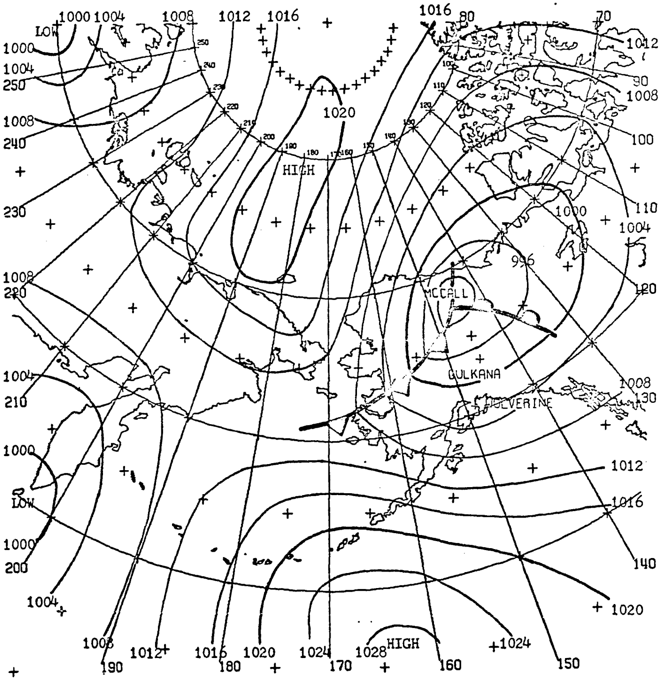

Figure 4-6. Surface weather map, 0000 GMT, 10 August 1969.

and deepened again. By 1200 GMT on the 12th it was located north of Victoria Island (Figure 4-7) with a secondary 500 mb low overhead. The principal 500 mb low was just southwest of Inuvik, N.W.T. About 20 mm w/e of snow fell on McCall Glacier in the 12 hour period ending at 1800 GMT on 12 August. It is thought that the long fetch over the Arctic Ocean, the probability of considerable open water there at this time of year, orographic uplift at the glacier, and the movement of the upper low all contributed to one extent or another to this substantial snowfall. These complexities reveal the difficulties that were sometimes encountered in determining the exact dynamic processes that brought snow to a particular glacier. Thus, much more detailed analysis would be required if more than just general statements concerning the history of an event are desired.

29-30 July 1971

Storm track J6 was associated with snowfalls on McCall Glacier on 29 and 30 July 1971. Analysis of the 6-hourly synoptic maps revealed that the snow that fell on McCall Glacier on 29 and 30 July was only partly a result of this storm. The event of 29 July was basically a simple cold front event (Figure 4-8). The low near Great Bear Lake in the figure was not directly associated with the cold front, but did merge with the low, not shown, from which the cold front extended. This merged low is shown on the map for 0000 GMT 30 July (Figure 4-9). For this event, though, the principal cyclone is that shown near 75° N, 150° W. This cyclone was born in the Northern Bering Sea and as such should be considered a Pacific storm. It first appeared on a map as a wave on the Arctic Front

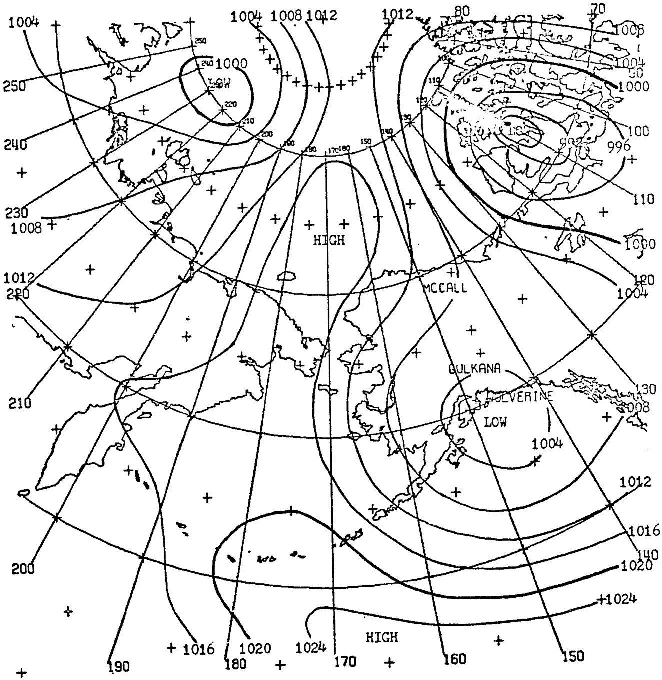

Figure 4-7. Surface weather map, 1200 GMT, 12 August 1969.

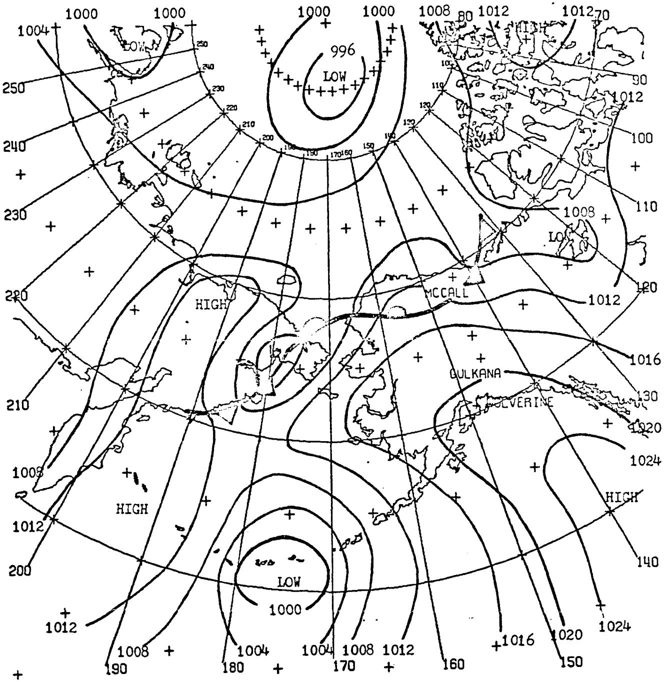

Figure 4-8. Surface weather map, 0000 GMT, 29 July 1971.

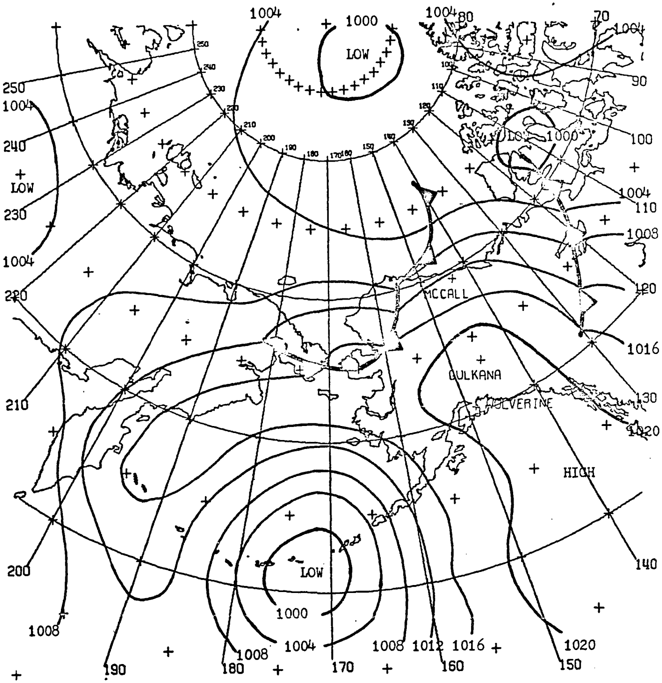

Figure 4-9. Surface weather map, 0000 GMT, 30 July 1971.

in the Northern Anadyr Gulf (~65° N, 178° W). From there it moved in a general northeastwards direction off the northwestern coast of Alaska. It decelerated NNE of Barrow but did not fill. By 0600 GMT 30 July, though, the now mature cyclone had intensified to a central pressure of 998 mb and moved to near 77° N, 144° W. The cold front shown associated with this cyclone lay near McCall Glacier by this time. Most of the snow for the 0000 GMT 30 July event fell between 0000 and 0600 GMT

15-16 July 1971

Storm track J5 formed as a result of cyclogenesis south of Inuvik, N.W.T. Snow associated with this track fell in three consecutive 12 hour periods starting at 1800 GMT 14 July 1971. In Figure 4-10 is shown the situation at 0000 GMT 15 July. The significant feature is the 1004 mb low near Inuvik, a low which first appeared on the 1800 GMT map for 14 July. Subsequent to the situation depicted in Figure 4-10 the low moved slowly northeastwards to lie near Cape Parry by 1200 GMT 15 July (Figure 4-11). The flow at McCall Glacier continued out of the north, varying from northeast to northwest. By 0000 GMT 16 July the low had drifted to Southern Banks Island, just east of Sachs Harbor (Figure 4-12). McCall Glacier continued to be influenced by the circulation around this low with the wind out of the northwest. Subsequencly, this low continued drifting northwards, eventually intensifying and rotating counterclockwise southwest of Prince Patrick Island. Simultaneously, clearing began to occur in Northern Alaska associated with a ridge of high pressure building from the west.

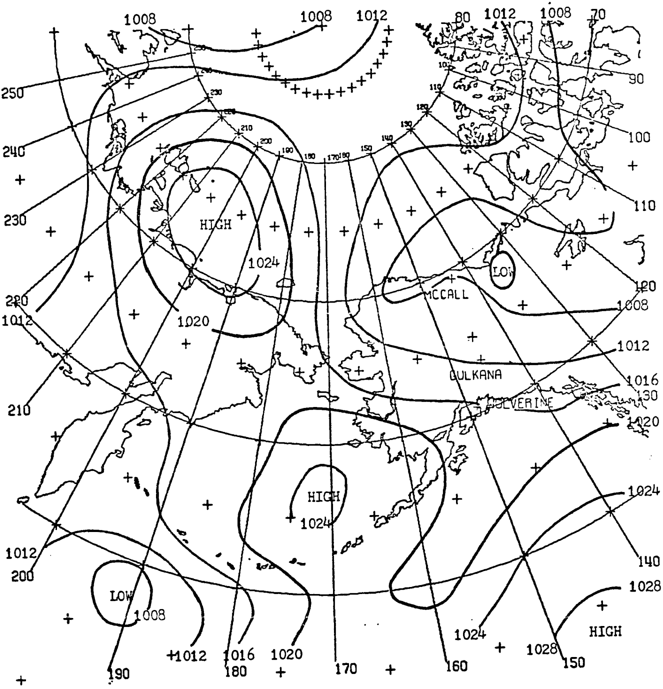

Figure 4-10. Surface weather map, 0000 GMT, 15 July 1971.

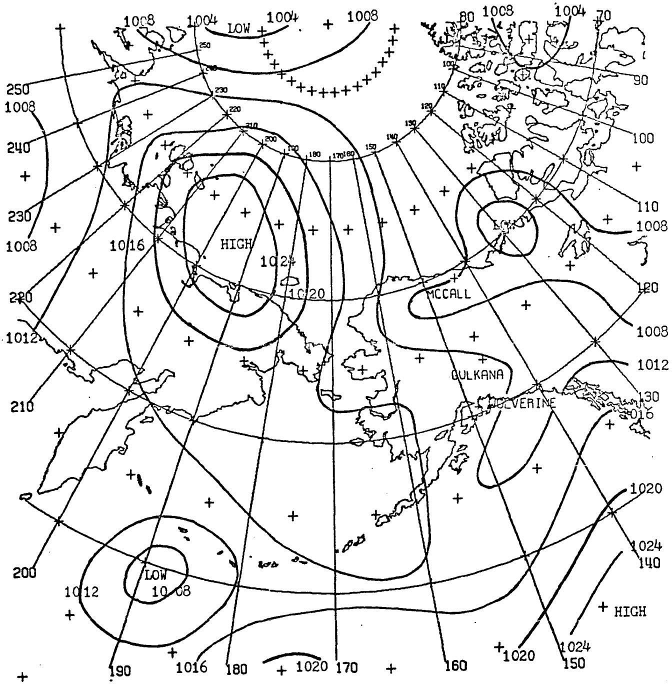

Figure 4-11. Surface weather map, 1200 GMT, 15 July 1971.

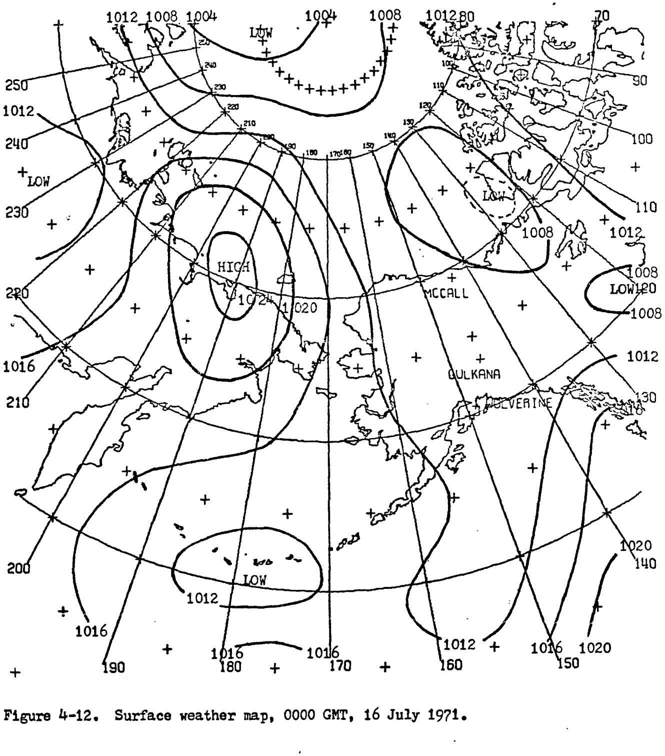

Figure 4-12. Surface weather map, 0000 GMT, 16 July 1971.

4.3.4 Summary

Benson (1967) has speculated that cyclones which traverse the Arctic Ocean from the Atlantic Ocean or that curve around the western and northern coasts of Alaska from the Pacific Ocean [due to blocking highs in the Gulf of Alaska and/or over mainland Alaska], release their moisture due to mechanical uplift near the Eastern Brooks Range. The event of 10-12 August would seem to be a candidate for such a model but did not contribute significant precipitation on 10 August. Perhaps its track was too far south over mainland Alaska. The storms of 29 and 30 July 1971, though, would seem to follow Benson's description.

Another model that would seem to be equally important in contributing accumulation to the Brooks Range involves storms that curve through the Canadian Archipelago either after genesis in extreme northwest Canada (e.g. the event of 15-16 July 1971) or regeneration in this area. The 10-12 August storm that did not contribute significant snowfall the 'first time around' did so after it regenerated in this area, thence curving north and west through the Canadian Arctic Islands. Storms that enter Interior Alaska from the Bering (and thus from the Pacific), and which frequently move eastward or northeastward into extreme northwestern Canada would also fit this model. This latter situation illustrates another way that Pacific storms contribute moisture to McCall Glacier.

Inspection of synoptic weather maps preceding and following particular events have revealed details that help illuminate the morphology of these events. At the same time, many complexities have appeared when MPM's are dissected to such an extent (e.g., the 10-12 August 1969 event). Perhaps the most valuable result from extending the basic MPM analysis has been the increased skill in interpreting the MPM's themselves. Identification of mean storm tracks, areas of cyclogenesis, etc., can now be made with more assurance.

CHAPTER 5

COMPARISON WITH OTHER STUDIES

5.1 Introduction

The value of any study can be measured at least partially, by comparison with previous studies. In the field relating glacier activity with climatic fluctuations very little exists with respect to mean sea level pressure patterns. There have been some studies though, on the form of mean pressure patterns that existed during the last great glaciation, the Wisconsin Glaciation. In so far as the MPM's produced here can be considered as representative of conditions during, before, or after a major glaciation a comparison with such studies would be useful. Another way the present study can be compared is indirectly. Thus, if a previous investigation has produced mean pressure maps according to different criteria, then, in so far as any of these maps are more representative or not than others of conditions favorable for glaciation, it would be useful to compare these maps with those produced here.

5.2 Girs' mean pressure maps based on 500 mb circulation types.

Girs (1966b) has produced maps which show the mean pressure patterns for the northern hemisphere for summer and winter for the nine combinations of the three 500 mb circulation types for each half of the hemisphere (see Section 2.3). He also gives maps of mean pressure anomalies and mean temperature anomalies. Girs' Figures 5-7 give the situation for summertime. MPM's # 1 and 2 were first compared to Girs' Figure 6, which shows the summertime distribution of mean pressure. For Girs' types E_Z and C_Z, a trough of low pressure was found in Central and Northern Alaska, extending into Northern Canada. In the E_Z type a mean low pressure center was indicated near Great Slave Lake, while in the C_Z type one slightly to the northeast was indicated, near 65° N, 105° W. These centers are further east than those found on MPM's # 1 and 2, but their existence along with the troughs makes these types the closest in form to MPM's # 1 and 2. Inspection of Girs' Figures 5 and 7 revealed that the largest negative anomalies of both temperature and pressure for the McCall and Gulkana Glacier regions occurred with the C_Z and E_Z types. This favorable comparison was strengthened by the results of Section 2.3, where a high frequency of Z type weather was correlated with colder and stormier weather on McCall Glacier.

None of the charts in Girs' Figure 5 showed positive pressure anomalies comparable to those shown on the MPM's for hot spells at Gulkana and Wolverine Glaciers (MPM's # 16 and 17, Figures A-16a and A-17a). The chart with the highest anomaly was that for the W_{M1} type of process, where pressure anomalies of ~$1\frac{1}{2}$ and 2 mb for Gulkana and Wolverine Glaciers respectively were indicated. Similarly, none of Girs' charts resembled the situation found for hot spells at McCall Glacier (cf. Figures A-15a and A-15b).

The situation for wintertime did not allow as successful a comparison. None of Girs' charts for mean winter pressure resembled the MPM for winter snowfall at Barter Island (MPM # 8, Figure A-8a). However, his chart for W_Z type processes did resemble the MPM's for winter snowfall at Gulkana and Wolverine Glaciers (MPM's # 9 and 10, Figures A-9a and A-10a). The Aleutian Low on his map was not elongated and had shifted to the west coast of Alaska, as in the case for the MPM's.

5.3 Lamb and Woodroffe's studies

Lamb and Woodroffe (1970) have derived sea level pressure distributions for both July and January for three stages of the last ice age. These stages were: 1) Würm (Wisconsin) ice age maximum, ca. 22 000 to 19 000 B.P.; 2) Allerӧd warm epoch, ca. 12 000 to 11 000 B.P.; and 3) Post-Allerӧd cold stage, ca. 10 500 B.P.

Considering first the July charts, a remarkable similarity was found between Lamb and Woodroffe's chart for July, 22 000 - 19 000 B.P. (their Figure 9a) and MPM # 1 (Figure A-1a). On their chart a 1005 mb low was shown near 72° N, 130° W, while on MPM # 1 a 1006 mb low was found near 70° N, 130° W. On the charts for July ca. 12 500 and 10 500 B.P. (their Figures 9b and 9c) this low was found shifted ~30° to the west. This pattern was unlike any found on the MPM's. Although the Allerӧd period was one of warming, the presence of the great ice sheets would have continued to influence circulation patterns. (the distribution of ice is shown on Lamb and Woodroffe's maps). Thus, the lack of similarity between Lamb and Woodroffe's chart for July, 12 500 B.P. and MPM's # 15, 16, or 17 (Figures A-15a, A-16a, and A-17a) was not unanticipated.

Their chart for January, 22 000 - 19 000 B.P. showed a 1010 mb low near 70° N, 120° W. Otherwise the patterns shown in the Alaska region were not that dissimilar from today's normal patterns (cf. Figure B-11). The MPM for the condition of winter snowfall at Barter Island (MPM # 8, Figure A-8a) shows a 1014 mb low near 70° N, 140° W. The implied storm track on MPM # 8 is around the western and northern coasts of Alaska. Lamb and Woodroffe (1970, p. 51) state that the "... main transport... entering the Arctic seems to have been from the Pacific over Alaska".

The implication from their chart 10a is a storm track from the Eastern Gulf of Alaska over the St. Elias Range. Due to the height of this range, the storm track indicated on MPM # 8 seems more likely. As in the case for July, their January circulation patterns for the Allerӧd and Post-Allerӧd periods did not have any counterparts in the MPM's presented here.

In so far as a mean low near 70° N, 130° W is a necessary condition for glaciation in the Brooks Range the similarities found between Lamb and Woodroffe's charts 9a and 10a and MPM's # 1 and 8 were gratifying.

5.4 Barry's climatic simulations based on the NCAR Global Circulation Model

Barry (1973) has modified the NCAR global circulation model to simulate the circulation at the last glacial maximum in January and July. The chart for July did not show a low near 70° N, 130° W but did show a trough of low pressure extending across Alaska. This trough, which would also be a first approximation of the storm track locus, extended from the 'glacial maximum' location of the Aleutian Low near 60° N, 190° W, to near 70° N, 150° W. There is approximate similarity between this chart and MPM's # 1 and 2.

Barry's chart for January was similar to that of Lamb and Woodroffe for the glacial maximum. A trough of low pressure extended in an arc from a low near 35° N, 140° W across the St. Elias Range to near 70° N, 140° W. A shorter trough was also shown off the west coast of Alaska, terminating near 65° N, 165° W. The inclusion of this latter trough allowed some similarity to MPM # 8.

5.5 Summary

The similarities outlined above were strong enough to increase the credibility of the MPM's. Because of the nature of the MPM's, being examples of extreme cases, exact comparability was not to be expected. One of the biggest differences between present day normal July charts and the ice age charts of Lamb and Woodroffe and Barry is the existence of a low pressure trough extending in a general northeasterly direction across Alaska. That such a feature was also found on MPM's # 1 and 2 tends to substantiate the 'truth' of these charts.

CHAPTER 6

CONCLUSION

6.1 Circulation patterns and weather systems that contribute to the growth or decay of glaciers in Alaska.

For all three glaciers it was found that growth occurred when the low level flow was from the nearest large body of water; there was an adequate supply of moisture. Decay occurred when these conditions were not met; there was not an adequate supply of moisture. Since the influx of moisture is expected of glacier growth, the fact that the MPM's for good circulations showed patterns favorable for moisture influx is a further proof that they are reasonable patterns. Flow from the direction of the nearest body of water was partially happenstance for McCall Glacier. Other bodies of water were moisture sources there, especially in the winter and spring. However, whatever the moisture source, most significant accumulations occurred if the low level flow was northerly. This direction allowed orographic uplift to operate and augment precipitation amounts. Due to the smaller annual totals of precipitation at McCall compared to Gulkana and Wolverine Glaciers, orographic uplift is a much more important precipitation augmenter there.

Synoptic patterns favorable for glacial growth were not the same for each glacier. A feature that favored growh of McCall Glacier was a blocking high over the Gulf of Alaska and/or mainland Alaska. Such a system resulted in decay of Gulkana and Wolverine Glaciers. However, glacial growth at all three glaciers is not necessarily a mutual exclusive activity. A proper alternation of individually favorably conditions for the three glaciers might occur in a particular year such that all three would experience a positive annual balance. The identification of the pattern that might be responsible for such an occurrence was not made here. Investigation of the hemispheric flow at higher levels would be required before such a pattern could be identified.

The circulation patterns and weather systems that contributed to the growth or decay for each glacier were found to be:

McCall Glacier

The situation at McCall Glacier was the most complex of the three glaciers. Conditions in the Beaufort Sea, northwest Canada, the Bering Sea, and the North Pacific Ocean can all be critical. Growth occurred when the patterns interacted to produce northerly flow at the glacier. A low in the Beaufort Sea to the north and/or to the east, as well as one in extreme northwestern Canada frequently occurred. A blocking high in the North Pacific Ocean steered storms around Alaska into the Arctic Ocean and was therefore a favorable pattern for growth. Decay occurred when the patterns produced southerly flow at the glacier. Such flow was drier as the air had passed over at least the Brooks Range, and possibly the Alaska and coastal ranges as well. In addition, orographic uplift could not enhance precipitation when the wind was from the south. A very strong Aleutian Low produced southerly flow. Such a strong low can be considered a manifestation of broader scale flow that restricts cyclonic activity north of the Alaska Range. Also, a strong Aleutian Low implies the compensatory formation of the Beaufort Sea High. In summertime, a strong Beaufort Sea High favored ablation, while in winter it hindered accumulation.

Gulkana Glacier

The Aleutian Low was the most critical circulation pattern affecting the growth of Gulkana Glacier. Growth occurred with southerly flow at the glacier. Moisture was brought by storms from the southwest. An eastward shift of the Aleutian Low was always observed. Decay occurred when these factors did not operate; thus, a westward shifted Aleutian Low was unfavorable. The buildup of the Beaufort Sea High in the summertime increased ablation on Gulkana Glacier.

Wolverine Glacier

Only circulation patterns in the Pacific Ocean affected growth and decay at Wolverine Glacier. Growth occurred when the Aleutian Low was very intense and shifted to the east. A slightly more southerly position of this low than found for Gulkana Glacier occurred. Southerly flow at Wolverine Glacier favored growth. Sometimes the flow had an easterly component also. When these conditions did not evolve, decay was favored. A strong blocking high in the North Pacific Ocean was the single most important feature whose appearance caused decay. In winter, it acted to steer storms away from the glacier, while in summer its appearance enhanced ablation.

6.2 The MPM's as an analytic tool in glacial/climatic investigations

The use of MPM's in other areas could be fruitful. Although the lack of actual data for particular glaciers or mountain ranges is not usually as acute elsewhere as it is in Alaska, the MPM approach would be beneficial in contributing to the overall knowledge of glaciers, climate, and their interactions. Monthly mean pressure charts have been produced by various national weather services for many years. These charts can be compared to MPM's and similar or dissimilar months can be found. Thus, those periods in the past there were favorable or unfavorable for glacial growth or decay can be identified. MPM's can also serve as guides for future trends towards or against glaciation. Most simply this can be done by noting trends, if any, in the mean monthly pressure patterns. If there is an increase in the frequency of mean monthly pressure patterns similar to favorable MPM's then glacier growth will be enhanced. A decrease in this frequency would lead to glacier decay. MPM's are more useful than other methods in indicating changes in hemispheric scale circulation and climate. For example, an eastward displacement in the Aleutian Low might imply a change in either wavelength or wavenumber of the flow at the 500 mb level.

An example of the use of MPM's as indicators of favorable/unfavorable glaciation conditions in the historic past is given below. The Extended Forecast Division's historic series of monthly charts for 1947-1971 were used. July charts were drawn from the EFD's gridded data for the case of summer snowfall at both McCall and Gulkana Glaciers.

Inspection of the 25 mean July charts revealed that eight were similar in one respect or another to MPM # 1 (Figure A-1a), the MPM for summer snowfall at McCall Glacier. These were 1953, 1959, 1961, 1963, 1964, 1965, 1967, and 1969. The three most similar, 1963, 1965, and 1969, are shown in Figures E-1, E-2, and E-3. Five years were found similar to MPM # 2 (Figure A-2a), the MPM for summer snowfall at Gulkana Glacier. These were 1948, 1953, 1964, 1965, and 1970. The most simiar month, July 1964, is shown in Figure E-4.

The preponderance of July's in the mid 1960's similar to the MPM's is reassuring. This period was found in Section 2.1 (cf. Figures 2-1 and 2-2) to be favorable for glacial activity in both the Brooks and Alaska Ranges.

The same procedure was followed in the case of hot spells. Figures E-5 and E-6 show the 1948 and 1958 June-July charts. Both these months were similar to MPM # 15, (Figure A-15a), the MPM for hot spells at Mc-Call Glacier. Figures E-7 and E-8 show two charts (1952 and 1968) similar to MPM #16 (Figure A-16a), the MPM for hot spells at Gulkana Glacier. Finally, Figures E-9 and E-10 show two charts (1953 and 1967) similar to MPM # 17 (Figure A-17a), the MPM for hot spells at Wolverine Glacier.

6.3 Suggestions for further work

An extension of the MPM approach of especial value would be the inclusion of upper levels. Gridded data for the 700 mb constant pressure surface are available from the EFD so that existing computer programs could be utilized with only minor changes. The use of 700 mb level data would presuppose hemispheric scale analysis. The problem of changes in the general circulation and in the global climate would then be addressed more directly than they were in this study.

The construction of the anomaly maps was time consuming. A beneficial refinement to the MPM approach reported here would thus be computerizing this aspect of the analysis. The inclusion of more events, such as bad events other than hot spells would be helpful.

Finally, some increased efforts in the non-MPM approach would further the understanding of the MPM's themselves, and thus increase the overall understanding of the relationship between climate and glaciers in Alaska.

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Commerce Clearinghouse for Federal Scientific and Technical Information, Springfield, Va.) 1966.

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APPENDIX A

APPENDIX A

MPM'S AND ASSOCIATED ANOMALY MAPS

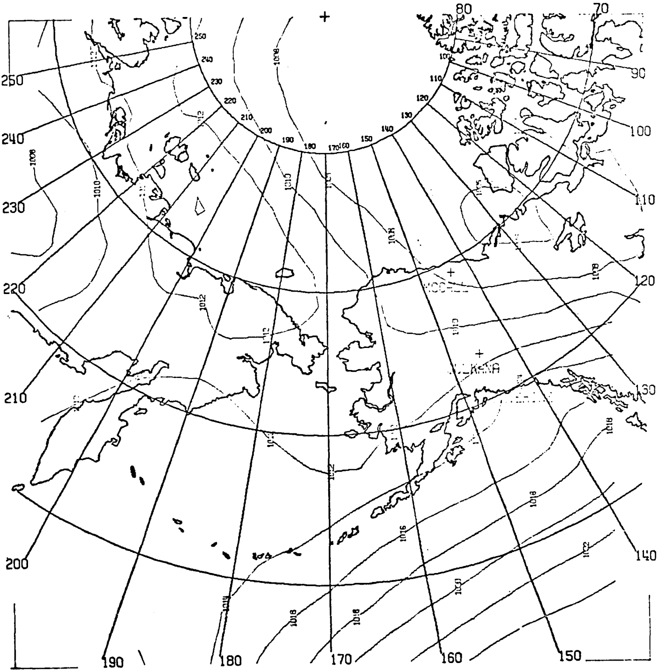

Figure A-1a. MPM #1. Mean pressure for 23 summer snowfalls (>2.5 mm w/e $12h^{-1}$), 1969-1972, McCall Glacier.

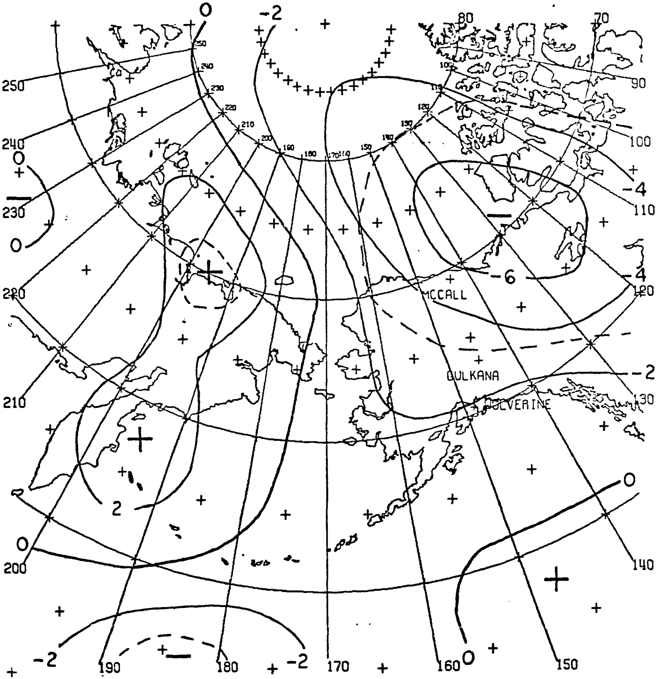

Figure A-1b. Mean pressure anomaly pattern associated with summer snow at McCall Glacier (July normals).

Pressure anomalies (2-mb intervals) from 1947-1971 mean. Broken lines enclose areas where anomalies are significantly different from zero at the 95% level according to t-test.

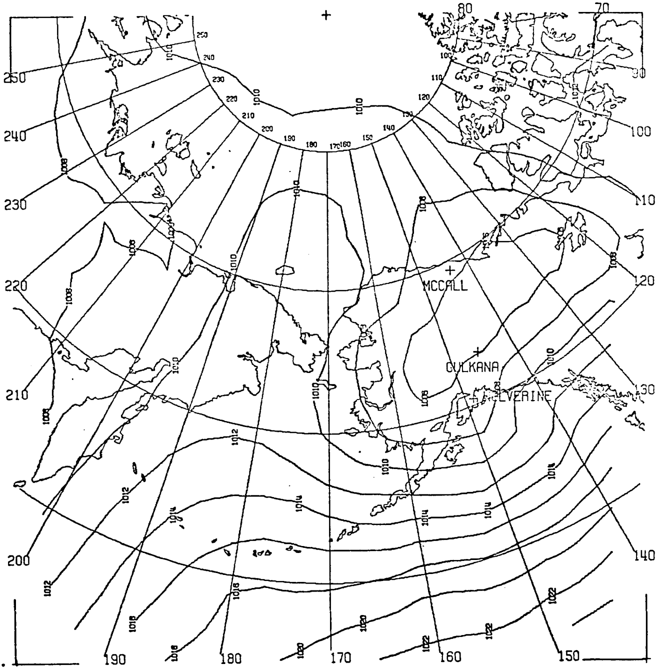

Figure A-2a. MPM #2. Mean pressure for 27 summer snowfalls (>7 mm w/e $12h^{-1}$), 1969-1972, Gulkana Glacier.

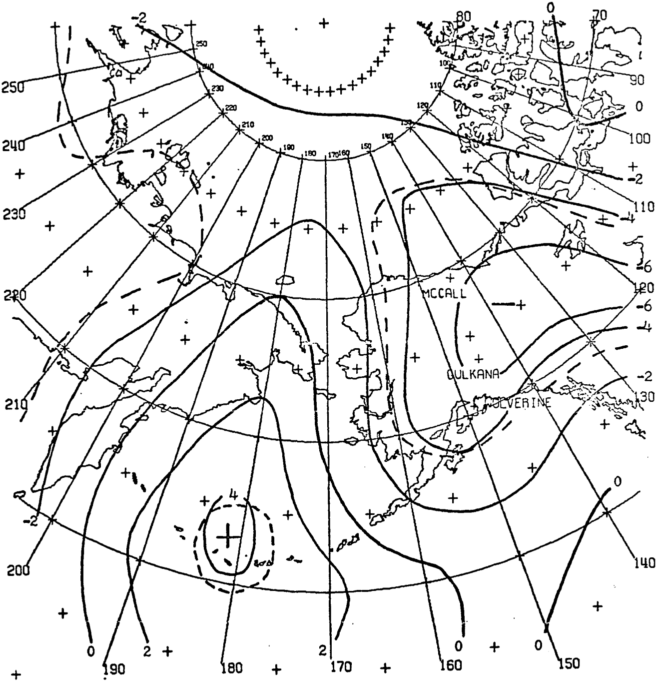

Figure A-2b. Mean pressure anomaly pattern associated with summer snow at Gulkana Glacier (August normals).

See note at foot of Figure A-1a.

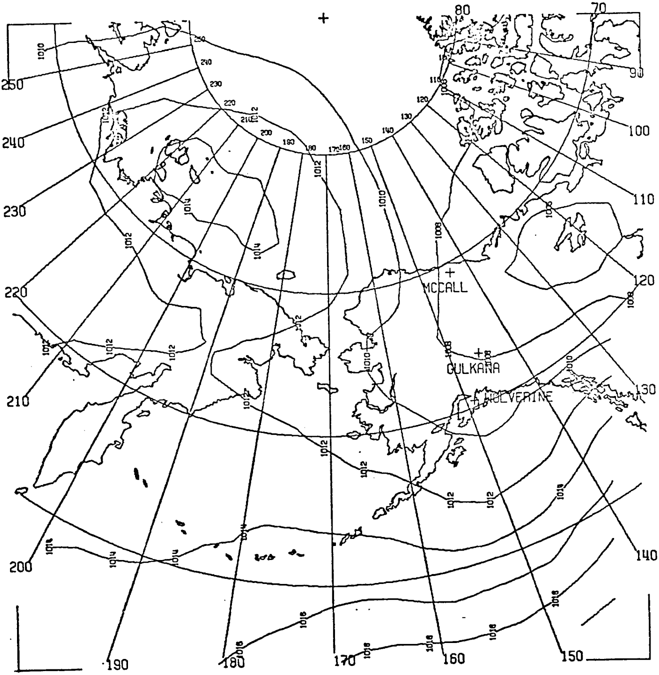

Figure A-3a. MPM #3. Mean pressure for 34 summer snowfalls (>2.5 mm w/e $12h^{-1}$), 1964-1972, Barter Island.

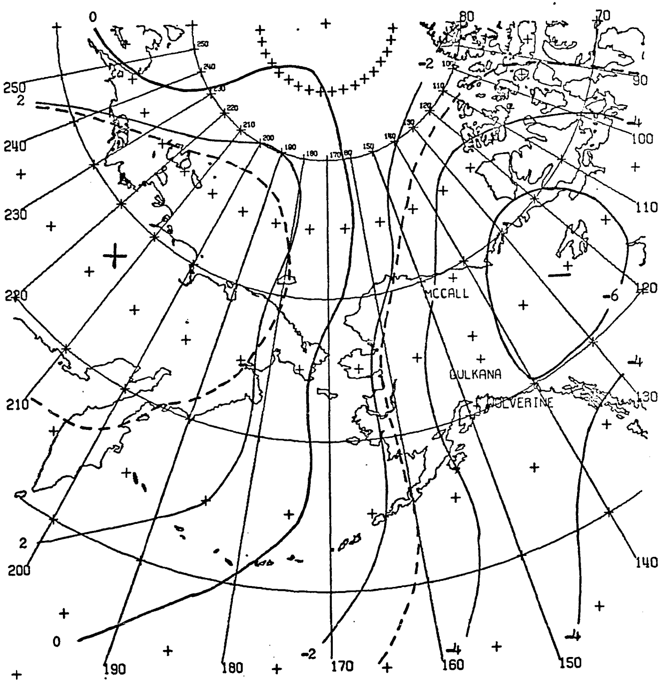

Figure A-3b. Mean pressure anomaly pattern associated with summer snow at Barter Island (July-August normals).

See note at foot of Figure A-1b.

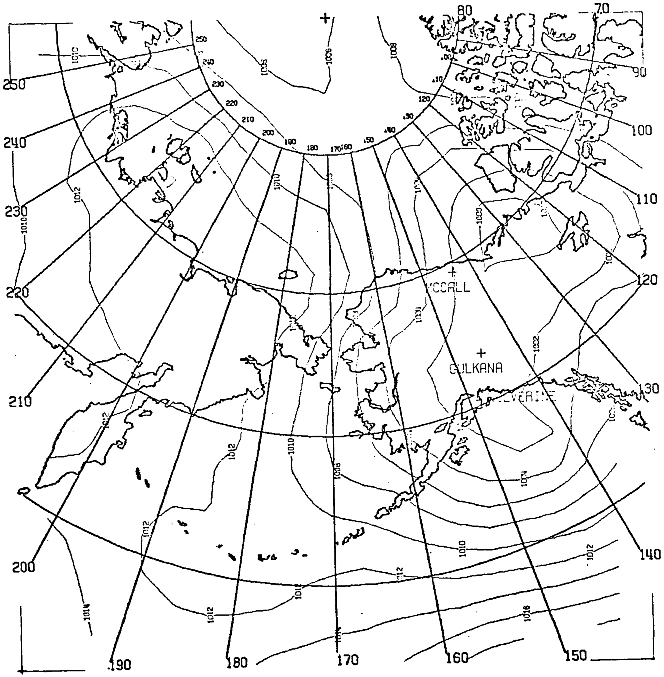

Figure A-4a. MPM #4. Mean pressure for 17 early fall snowfalls (>2.5 mm w/e $12h^{-1}$), 1969-1971, McCall Glacier.

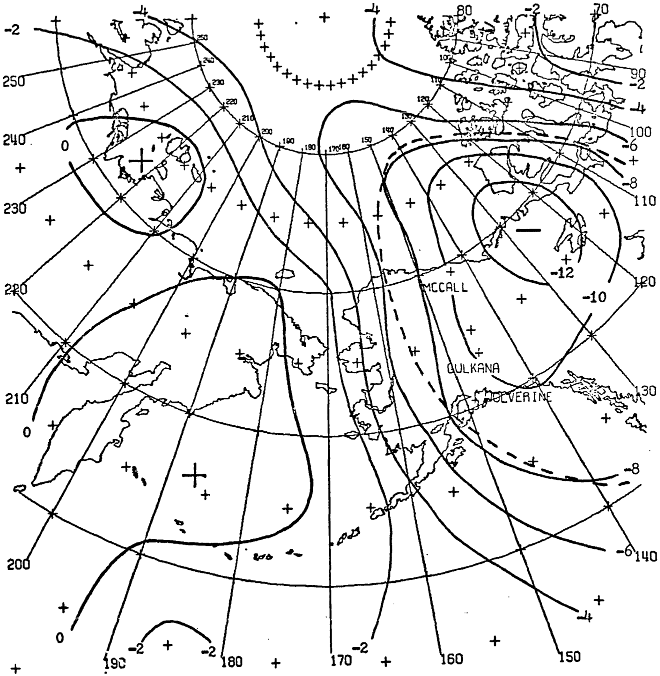

Figure A-4b. **Mean pressure anomaly pattern associated with early fall snow at McCall Glacier (August-September normals).**

See note at foot of Figure A-1b.

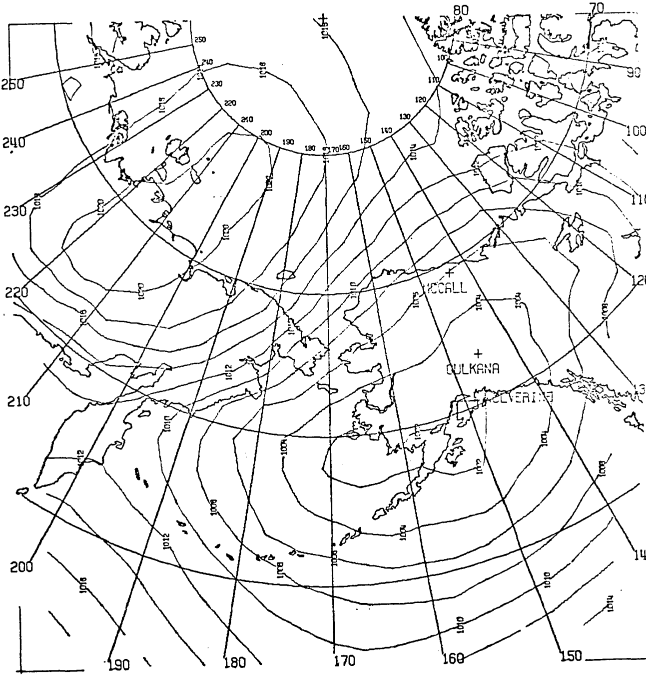

Figure A-5a. MPM #5. Mean pressure for 35 fall snowfalls (>1.3 mm w/e $12h^{-1}$), 1968-1972, Barter Island.

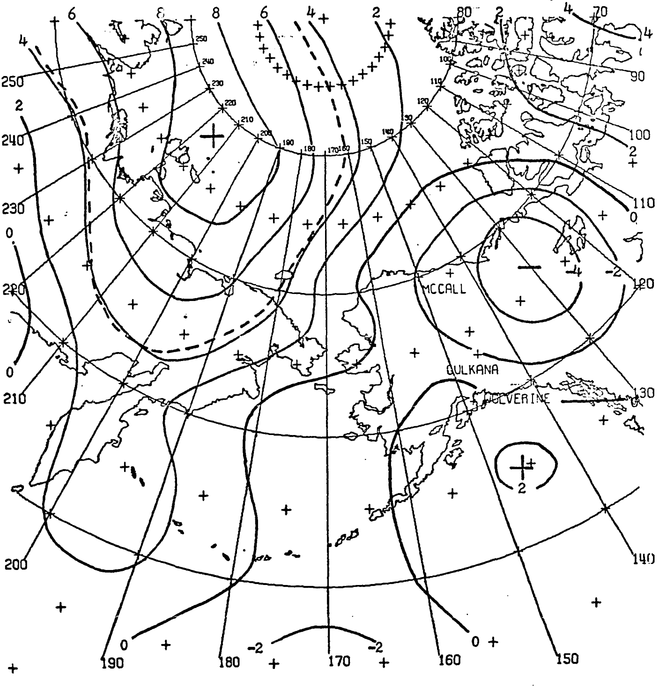

Figure A-5b. Mean pressure anomaly associated with fall snow at Barter Island (October normals).

See note at foot of Figure A-1b.

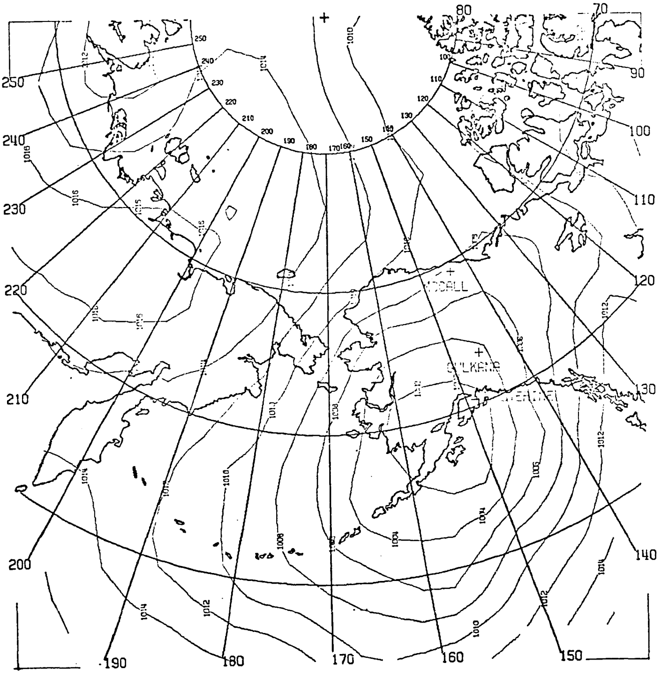

Figure A-6a. MPM #6. Mean pressure for 26 fall snowfalls (>7mm w/e $12h^{-1}$), 1967-1971, Gulkana Glacier.

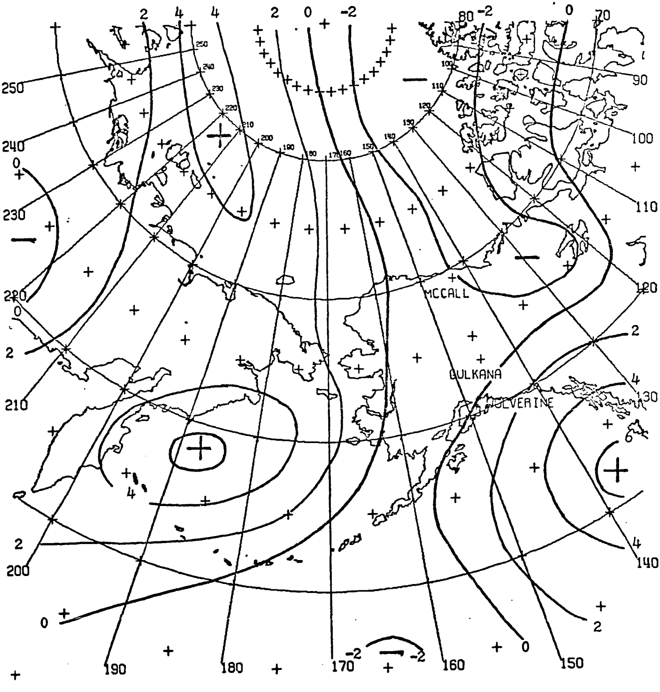

Figure A-6b. Mean pressure anomaly pattern associated with fall snow at Gulkana Glacier (October normals).

See note at foot of Figure A-1 b.

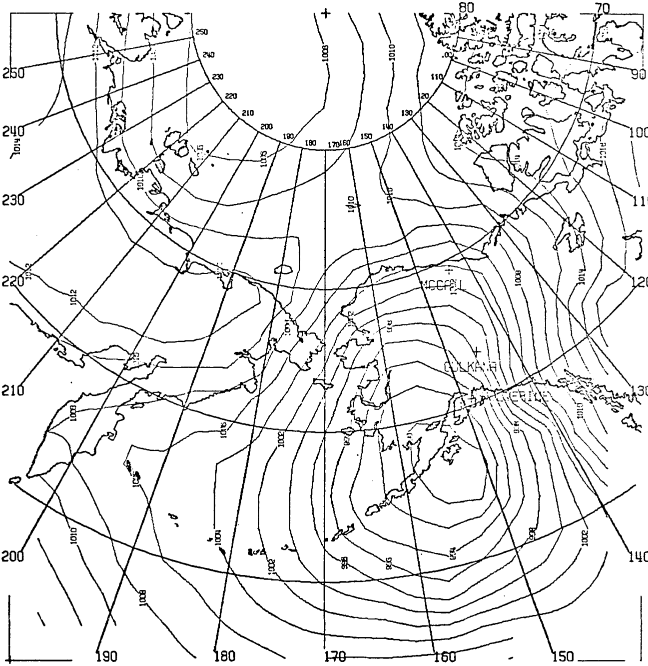

Figure A-7a. MPM #7. Mean pressure for 17 fall snowfalls (>10mm w/e $12h^{-1}$), 1967-1971, Wolverine Glacier.

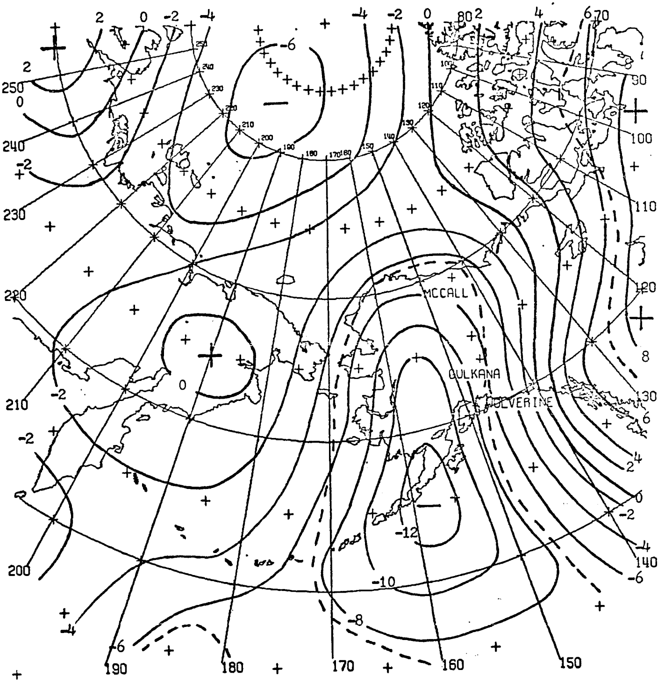

Figure A-7b. **Mean pressure anomaly pattern associated with fall snow at Wolverine Glacier (October normals).**

See note at foot of Figure A-1 b.

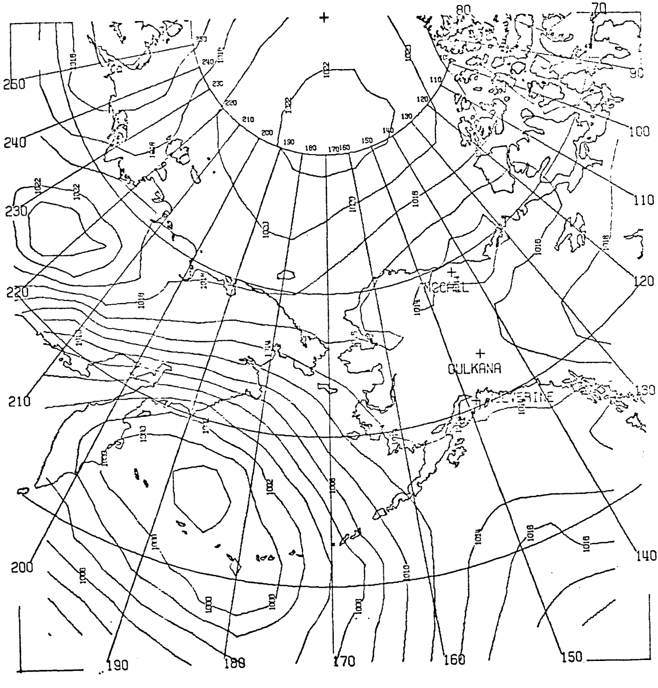

Figure A-8a. MPM #8. Mean pressure for 29 winter snowfalls (>1.3mm w/e $12h^{-1}$), 1967/68-1971/72, Barter Island.

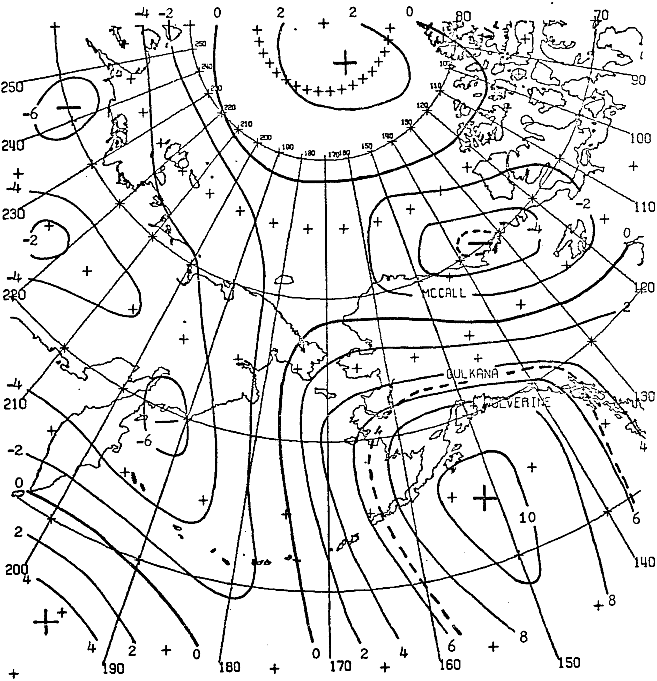

Figure A-8 b. Mean pressure anomaly pattern associated with winter snow at Barter Island ((December + Februaty)/2 normals).

See note at foot of Figure A-1 b.

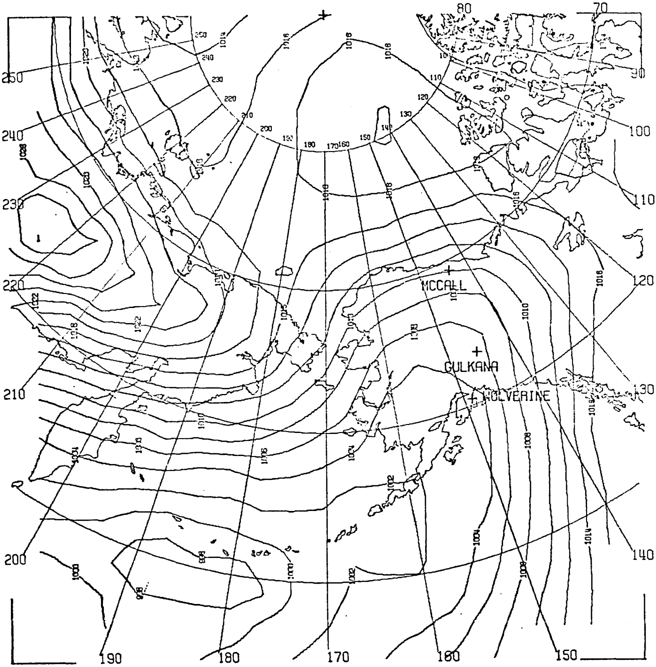

Figure A-9a. MPM #9. Mean pressure for 29 winter snowfalls (>10mm w/e $12h^{-1}$), 1967/68-1971/72, Gulkana Glacier.

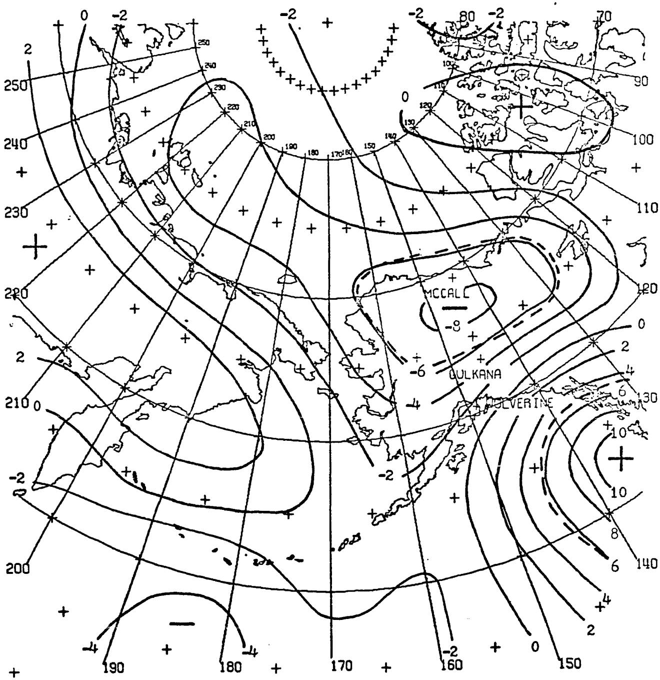

Figure A-9b. Mean pressure anomaly pattern associated with winter snow at Gulkana Glacier ((December + February)/2 normals).

See note at foot of Figure A-1b.

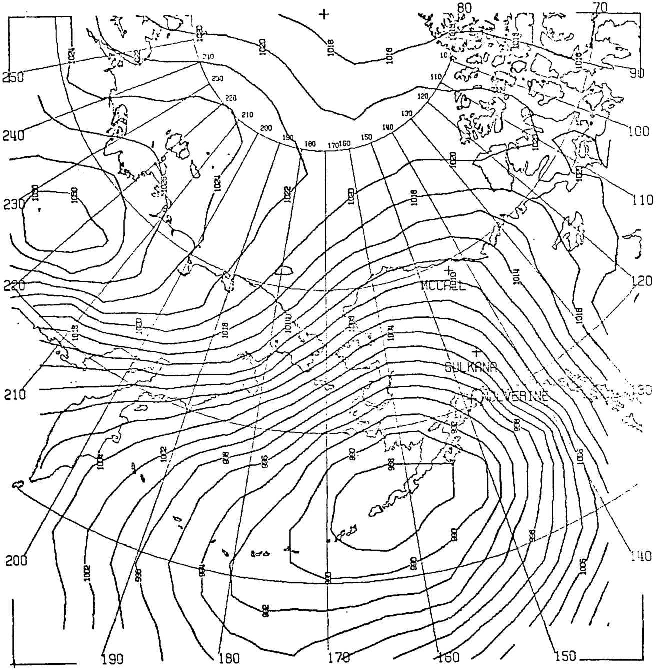

Figure A-10a. MPM #10. Mean pressure for 22 winter snowfalls (>10mm w/e 12h^{-1}), 1967/68-1971/72, Wolverine Glacier.

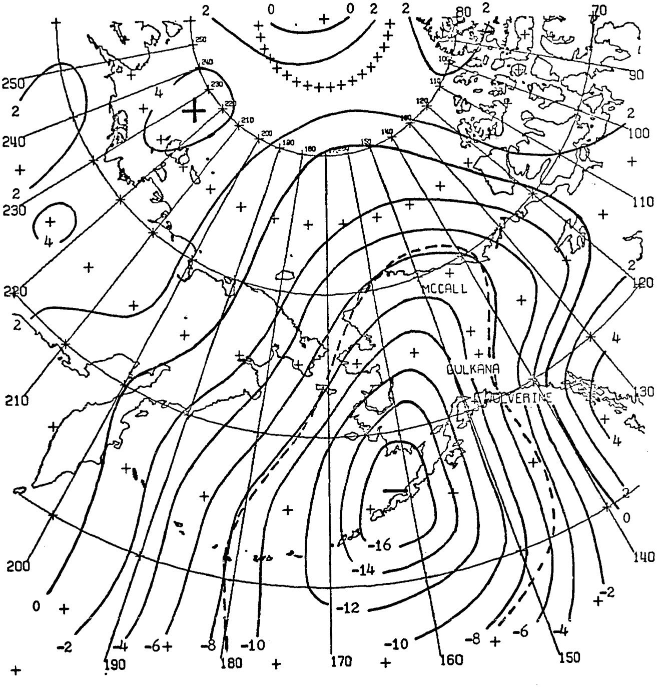

Figure A-10b. **Mean pressure anomaly pattern associated with winter snow at Wolverine Glacier ((December + February)/2 normals).**

See note at foot of Figure A-1b.

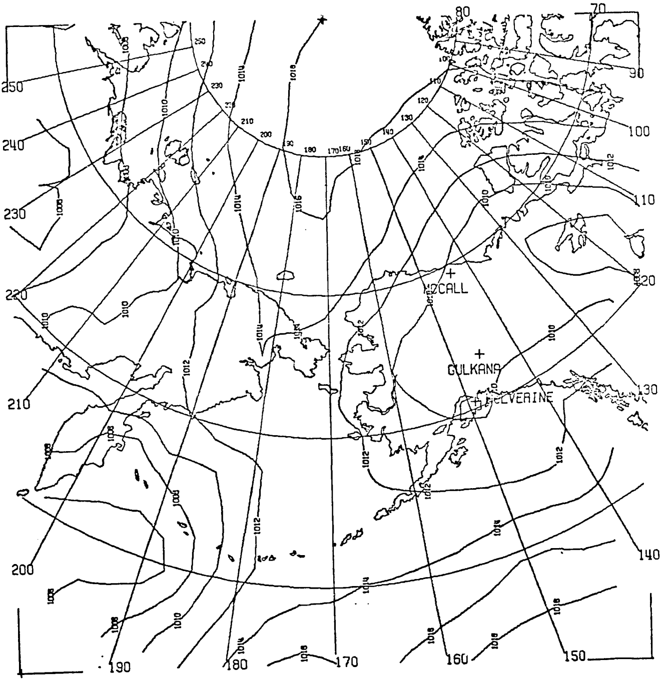

Figure A-11a. MPM #11. Mean pressure for 18 spring snowfalls (>2.5mm w/e $12h^{-1}$), 1970-1972, McCall Glacier.

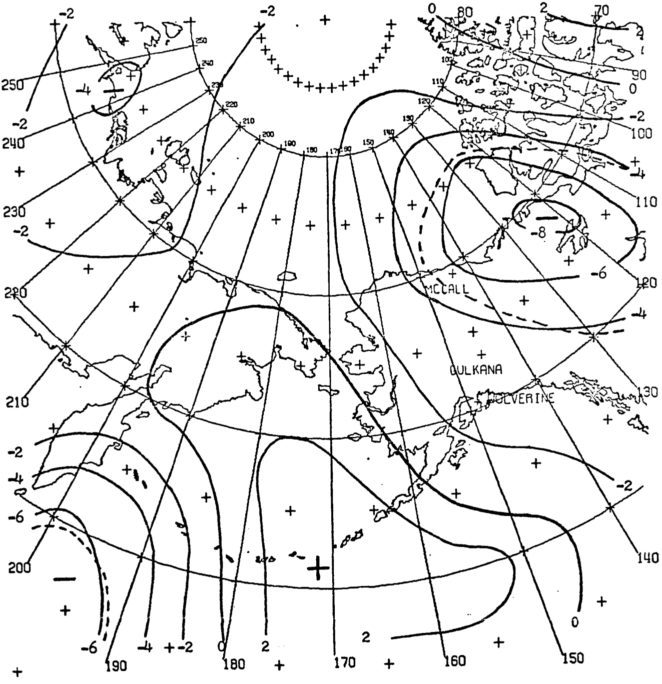

Figure A-11b. Mean pressure anomaly pattern associated with spring snow at McCall Glacier (May-June normals).

See note at foot of Figure A-1b.

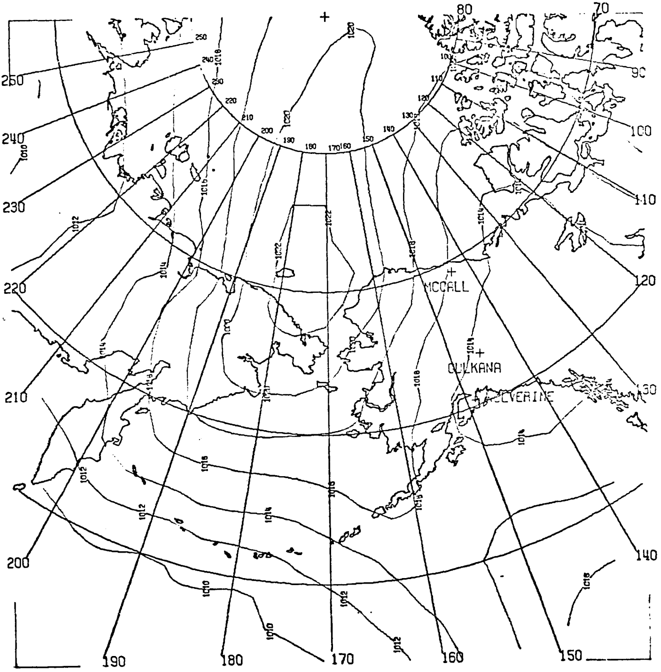

Figure A-12a. MPM #12. Mean pressure for 23 spring snowfalls (>1.3mm w/e $12h^{-1}$), 1968-1972, Barter Island.

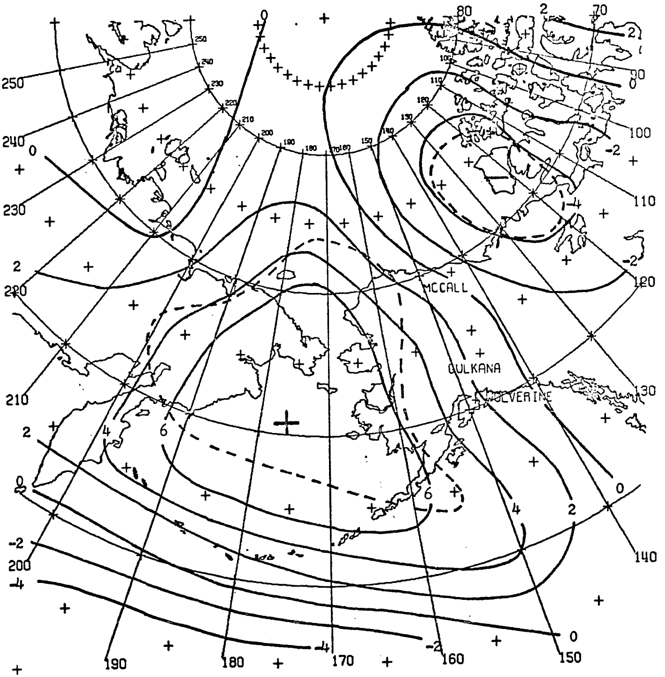

Figure A-12b. **Mean pressure anomaly pattern associated with spring snow at Barter Island (May normals).**

See note at foot of Figure A-1b.

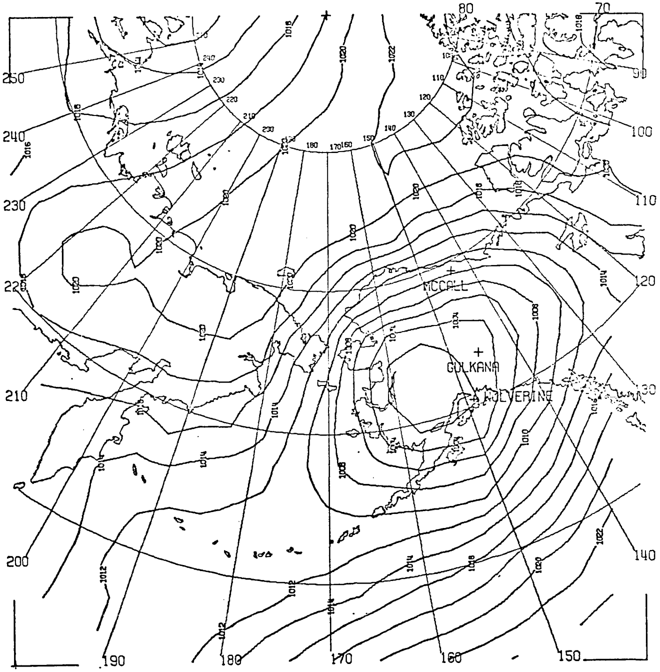

Figure A-13a. MPM #13. Mean pressure for 16 spring snowfalls (>7mm w/e $12h^{-1}$), 1968-1972, Gulkana Glacier.

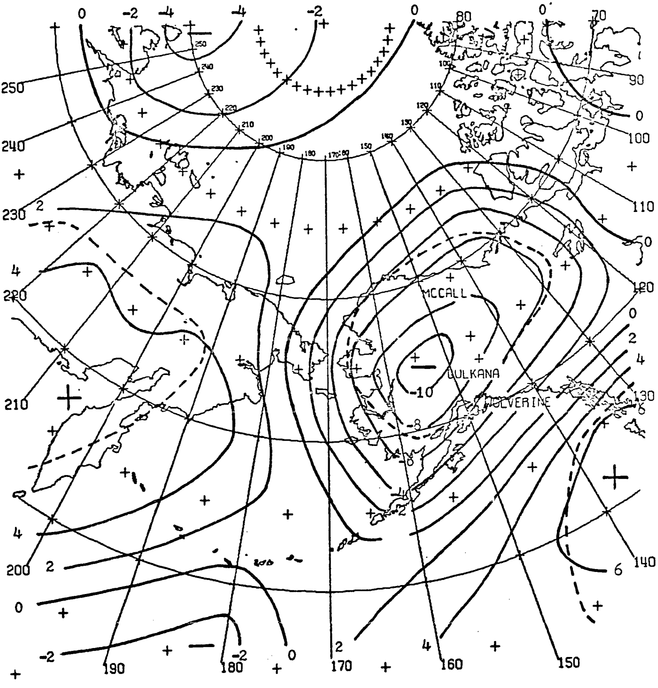

Figure A-13b. **Mean pressure anomaly pattern associated with spring snow at Gulkana Glacier (April normals).**

See note at foot of Figure A-1b.

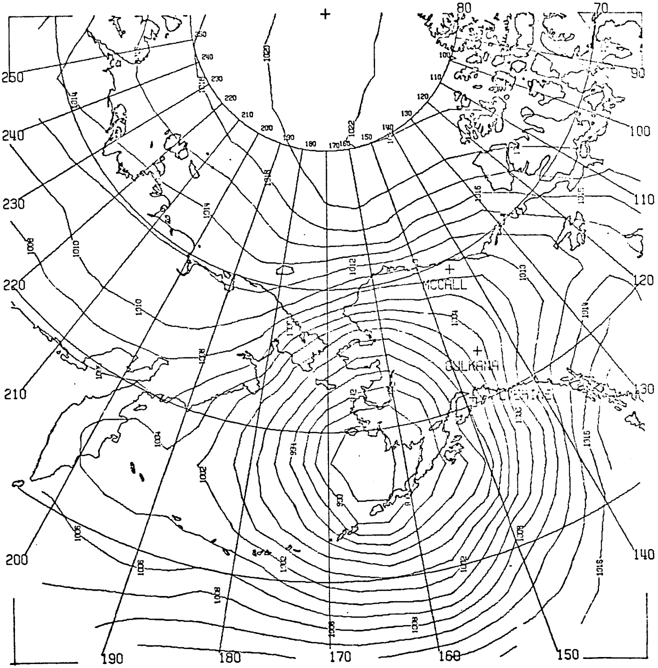

Figure A-14a. MPM #14. Mean pressure for 11 spring snowfalls (>10mm w/e $12h^{-1}$), 1968-1972, Wolverine Glacier.

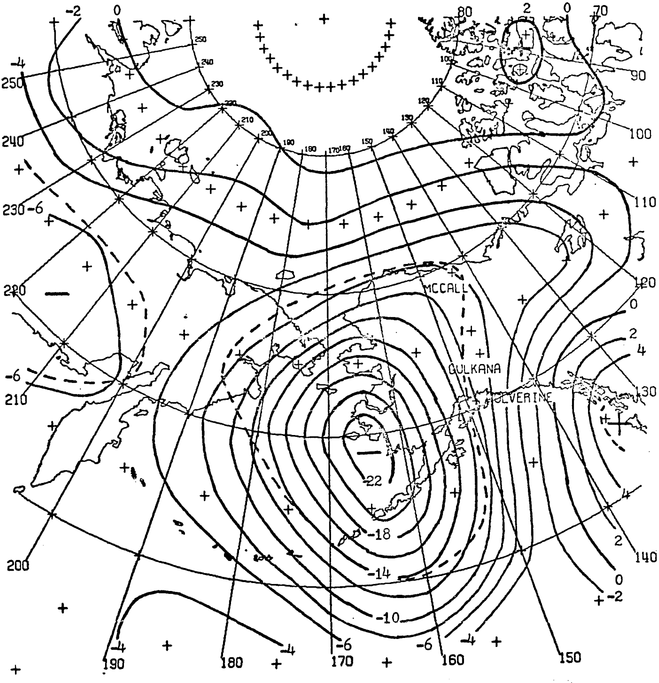

Figure A-14b. Mean pressure anomaly pattern associated with spring snow at Wolverine Glacier (April normals).

See note at foot of Figure A-1b.

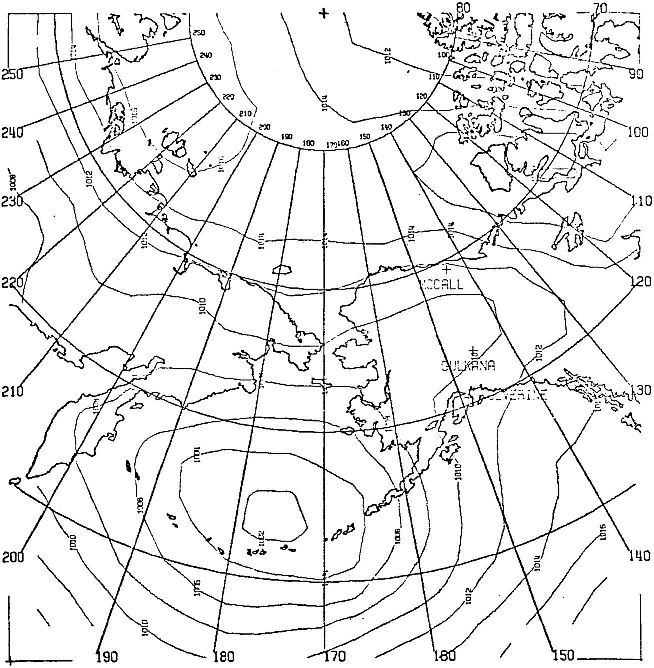

Figure A-15a. MPM #15. Mean pressure for 12 (28 12h periods) hot spells (T >8.4°C), 1969-1972, McCall Glacier.

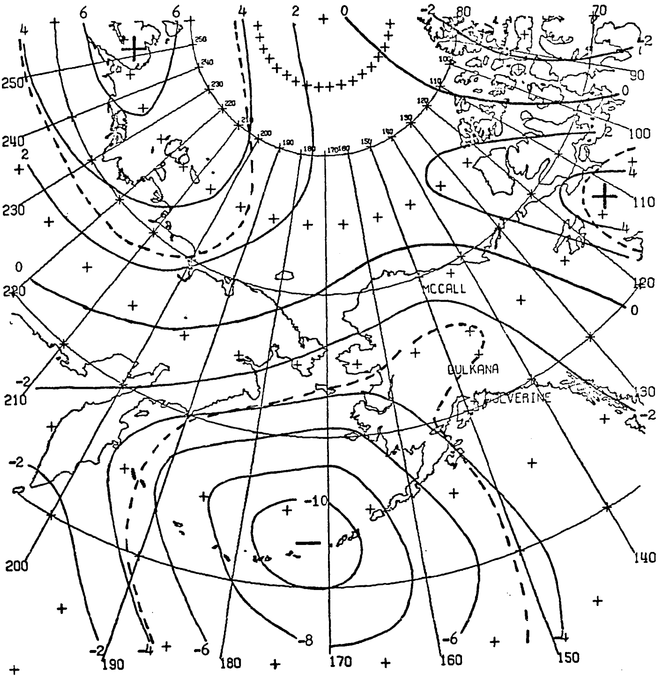

Figure A-15b. Mean pressure anomaly pattern associated with hot spells at McCall Glacier (June-July normals).

See note at foot of Figure A-1b.

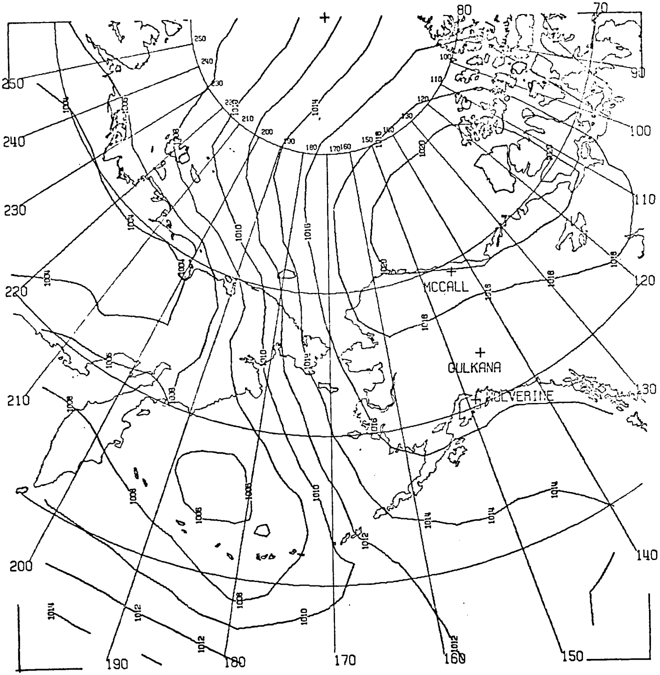

Figure A-16a. MPM #16. Mean pressure for 10 (31 12h periods) hot spells ($\bar{T}$ >11.9°C), 1968-1972, Gulkana Glacier.

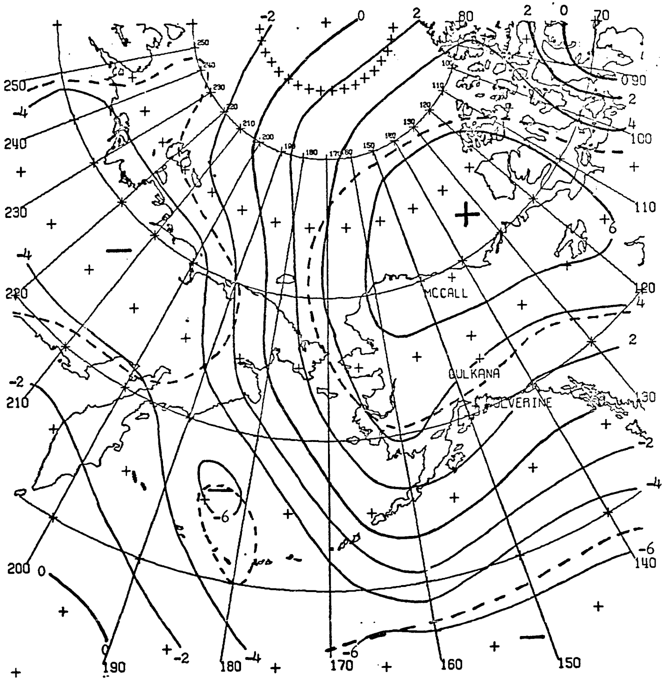

Figure A-16b. Mean pressure anomaly pattern associated with hot spells at Gulkana Glacier (June-July normals).

See note at foot of Figure A -1 b.

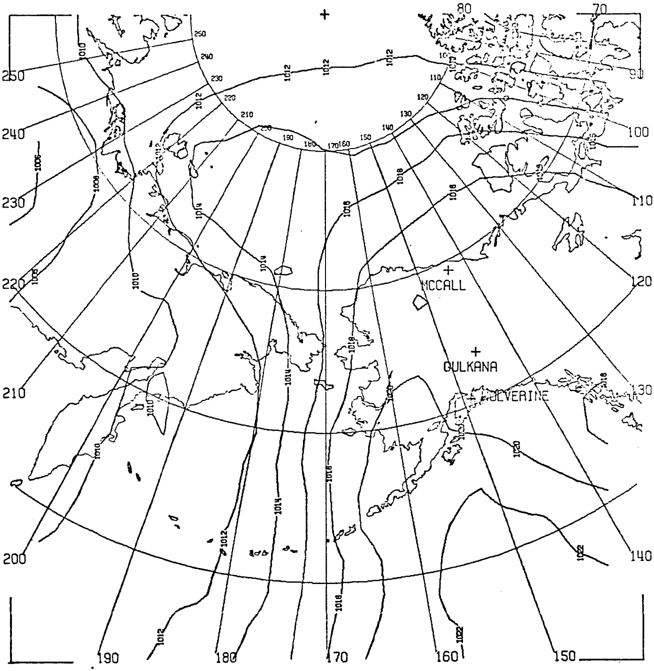

Figure A-17a. MPM #17. Mean pressure for 11 (33 12h periods) hot spells ($\bar{T}$ >12.9°C), 1967-1972, Wolverine Glacier.

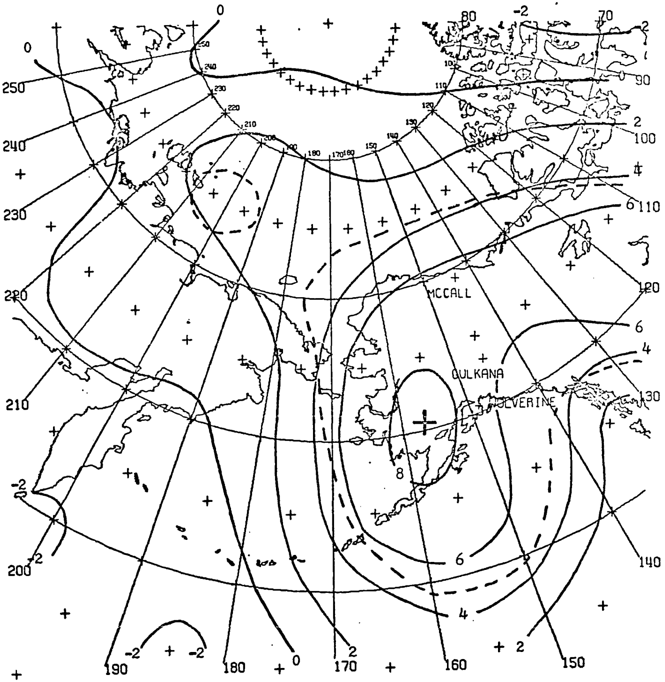

Figure A-17b. Mean pressure anomaly pattern associated with hot spells at Wolverine Glacier (June-July normals).

See note at foot of Figure A-1b.

APPENDIX B

APPENDIX B

25 - YR MEAN (NORMAL) MONTHLY PRESSURE MAPS

Figure | Page

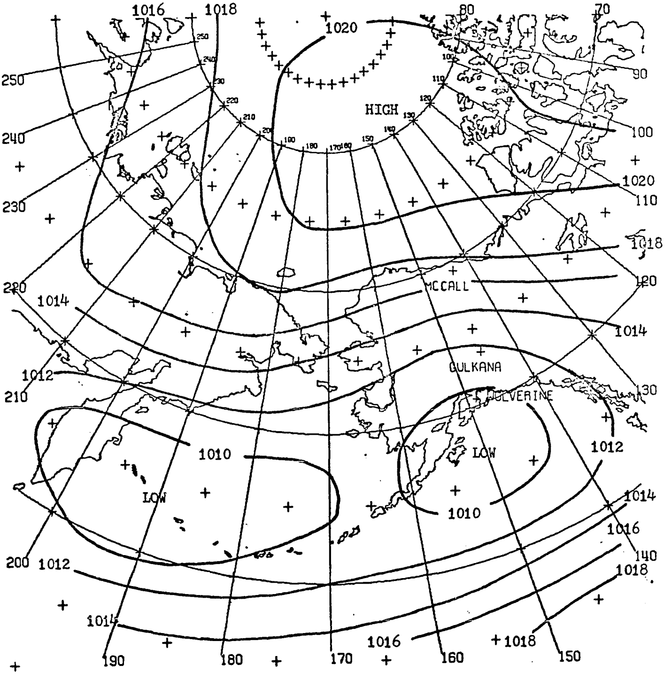

Figure B-1. 25-year mean sea level pressure (mb) April 1947-1971.

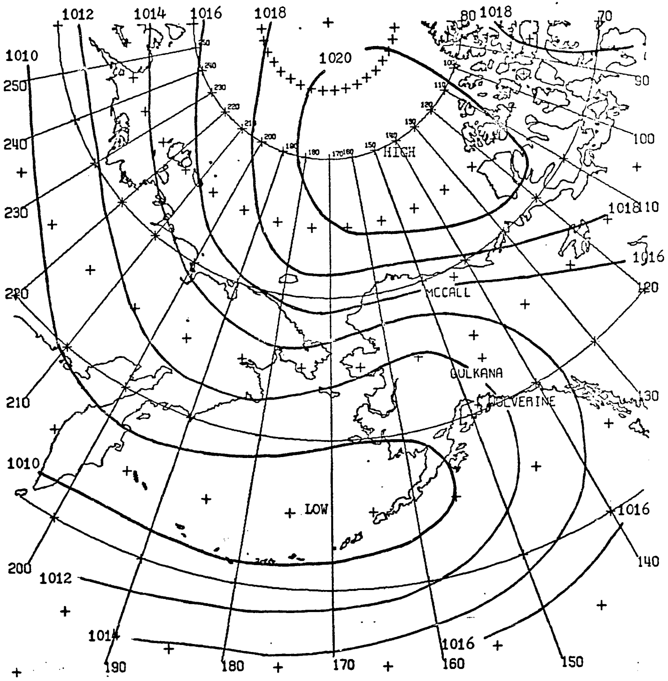

Figure B-2. 25-year mean sea level pressure (mb) May 1947-1971.

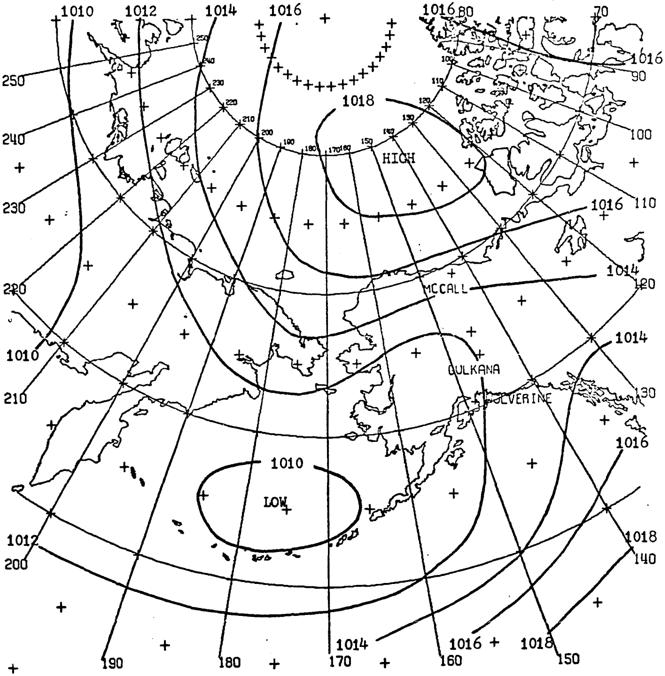

Figure B-3. 25-year mean sea level pressure (mb) May-June 1947-1971.

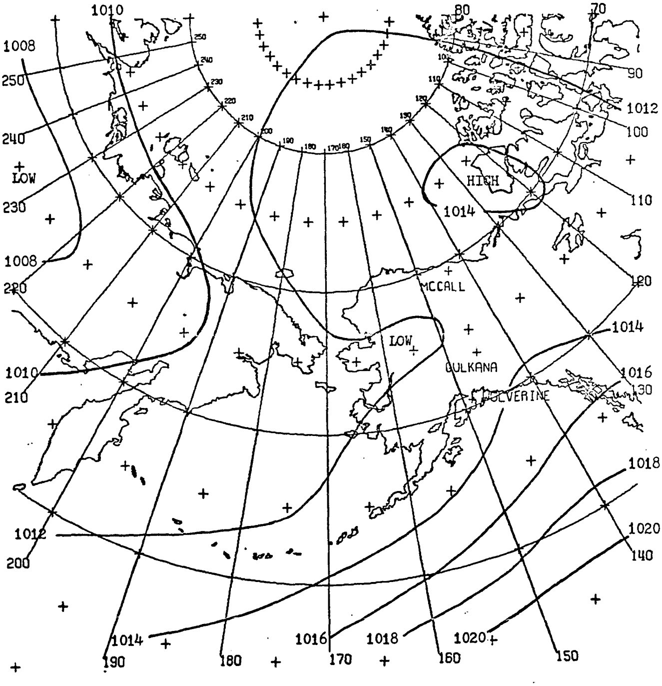

Figure B-4. 25-year mean sea level pressure (mb) June-July 1947-1971.

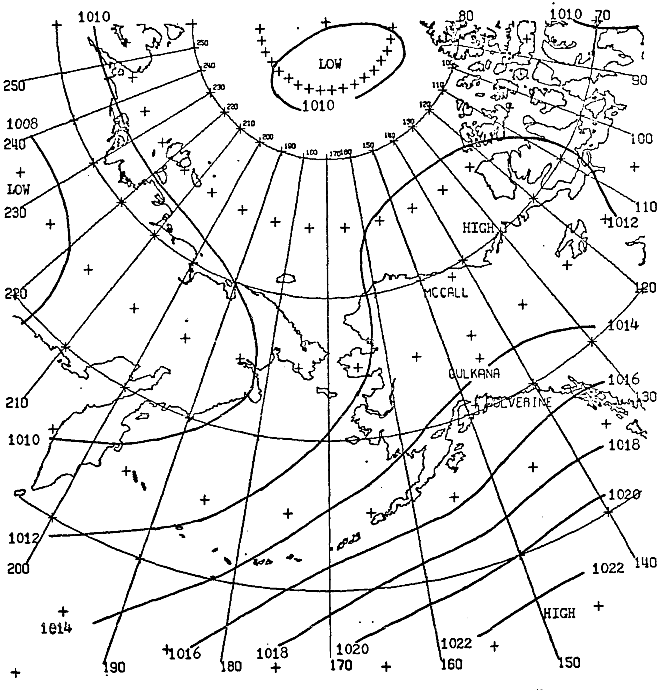

Figure B-5. 25-year mean sea level pressure (mb) July 1947-1971.

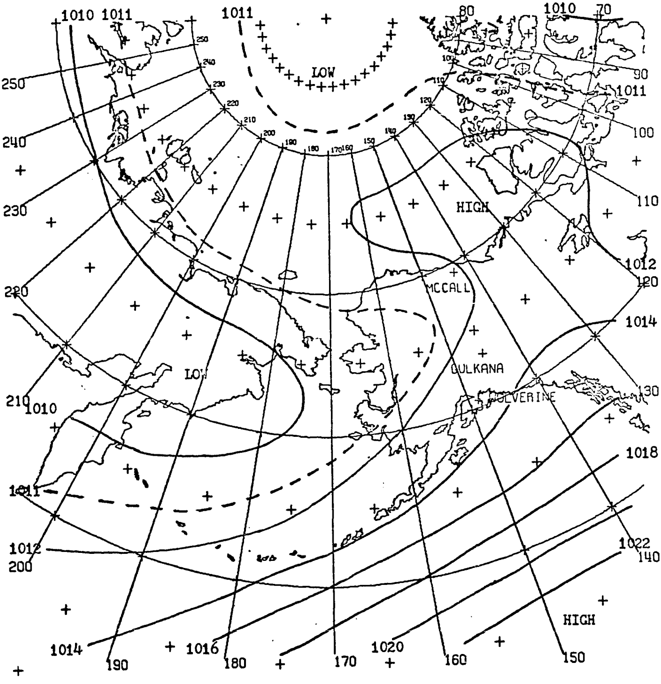

Figure B-6. 25-year mean sea level pressure (mb) July-August 1947-1971.

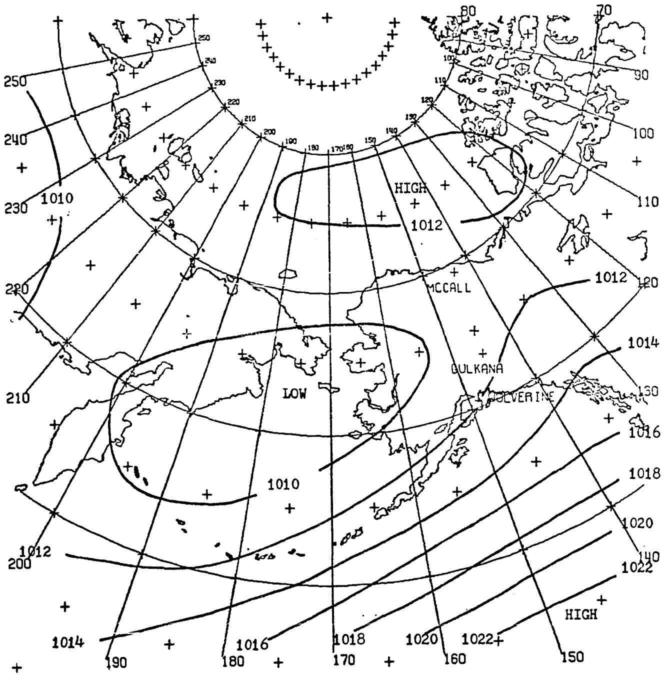

Figure B-7. 25-year mean sea level pressure (mb) August 1947-1971.

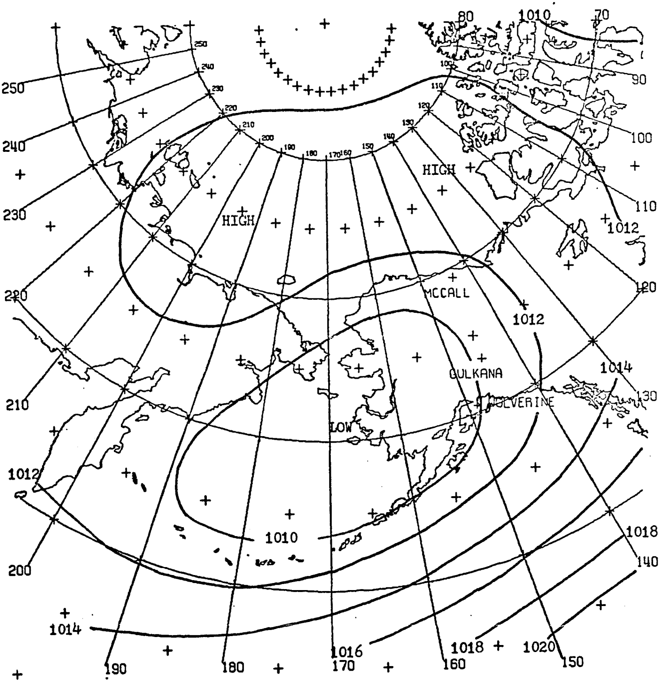

Figure B-8. 25-year mean sea level pressure (mb) August-September 1947-1971.

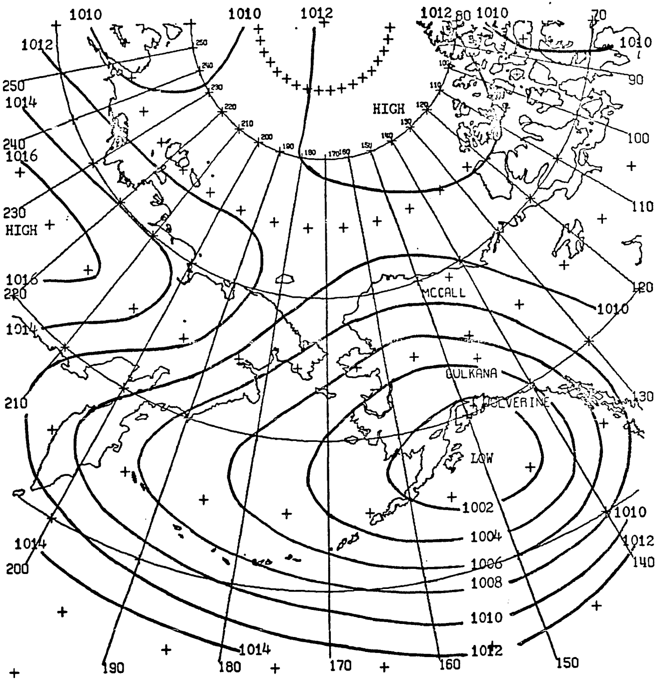

Figure B-9. 25-year mean sea level pressure (mb) October 1947-1971.

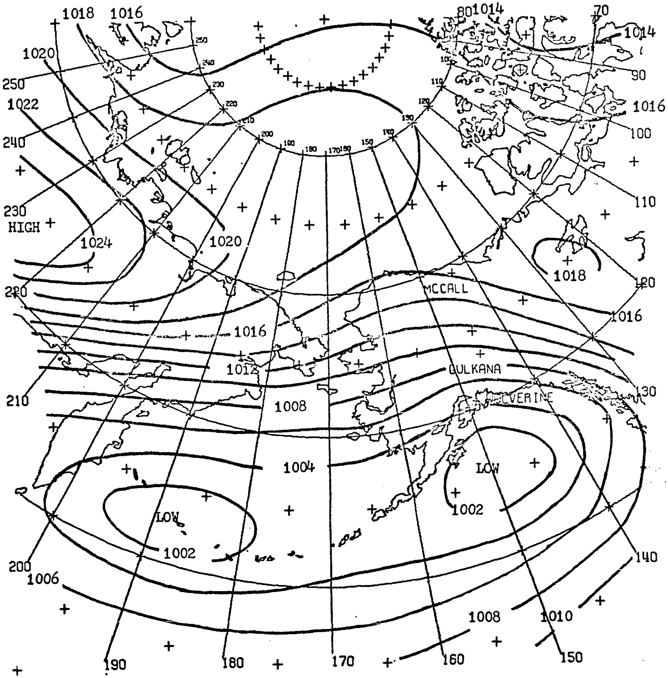

Figure B-10. 25-year mean sea level pressure (mb) December 1947-1971.

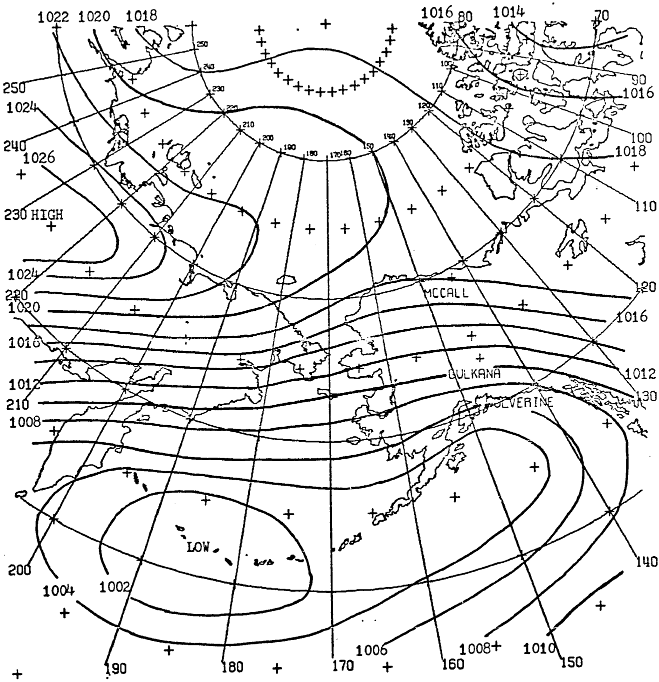

Figure B-11. 25-year mean sea level pressure (mb) (December + February)/2 1947-1971.

APPENDIX C

APPENDIX C

STANDARD PRESSURE DEVIATION MAPS

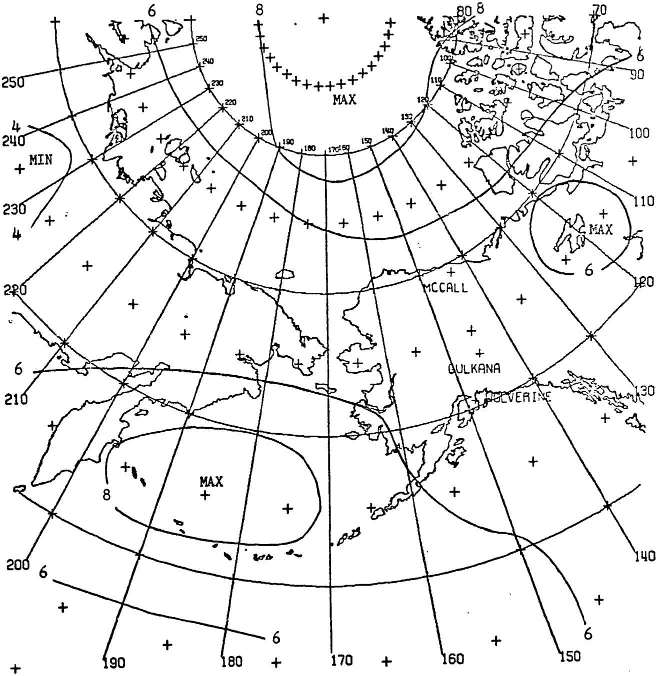

Figure C-1. Standard deviation of pressure for July for the Alaska Region.

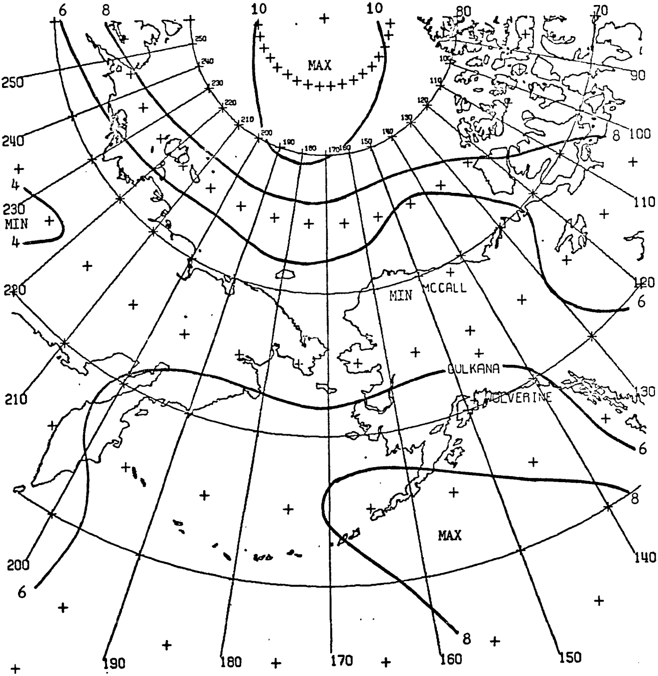

Figure C-2. Standard deviation of pressure for August for the Alaska Region.

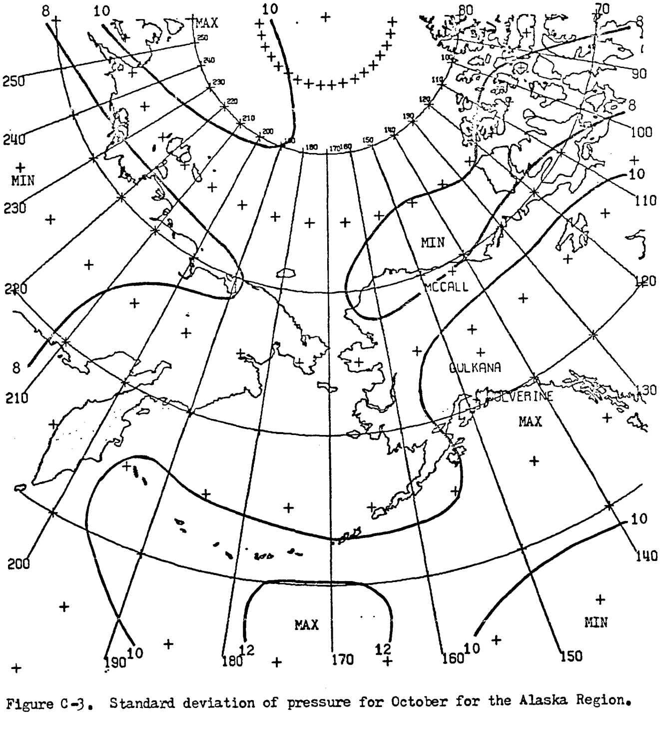

Figure C-3. Standard deviation of pressure for October for the Alaska Region.

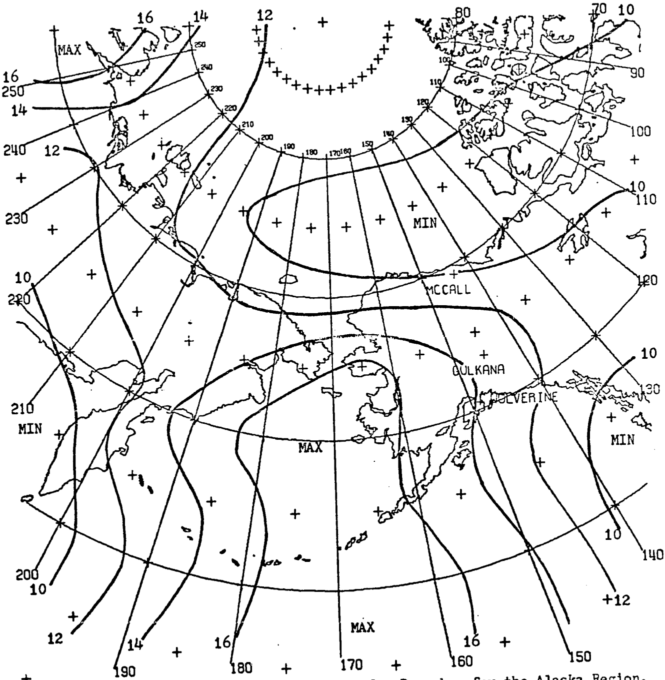

Figure G-4. Standard deviation of pressure for December for the Alaska Region.

APPENDIX D

APPENDIX D

TYPICAL EVENT MAPS

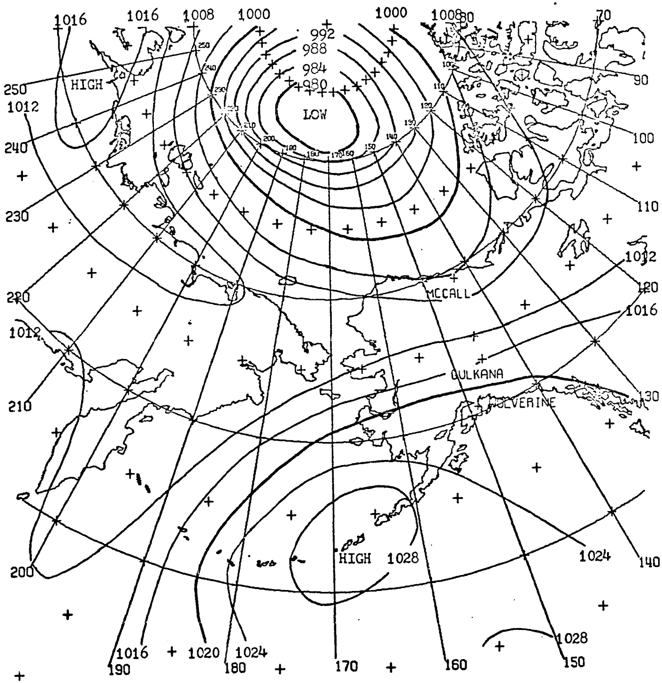

Figure D-1. Typical MS1 event: 1200 GMT 2 August 1969.

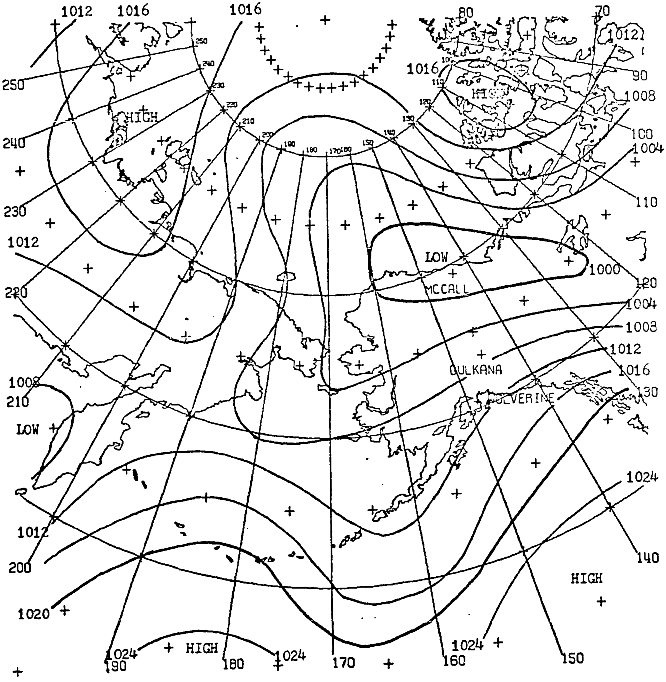

Figure D-2. Typical MS2 event: 0000 GMT 31 July 1970.

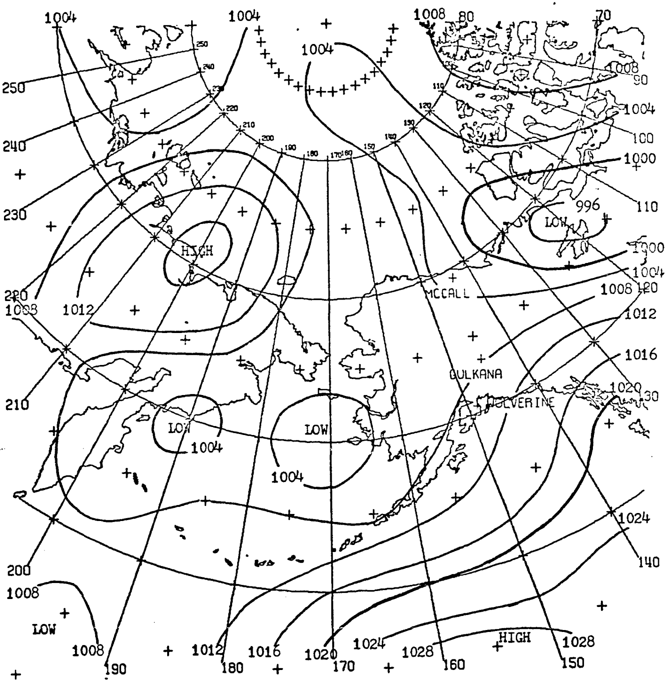

Figure D-3. Typical MS3 event: 1200 GMT 8 July 1970.

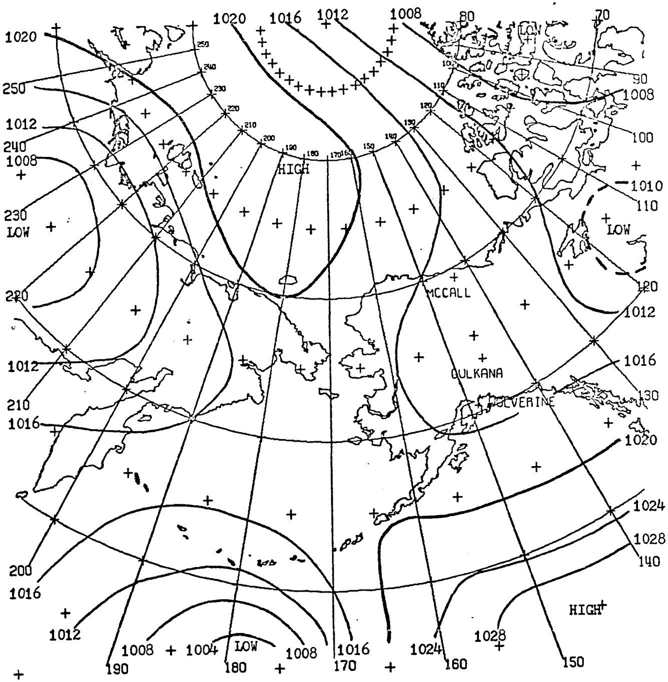

Figure D-4. Typical MS4 event: 1200 GMT 21 June 1972.

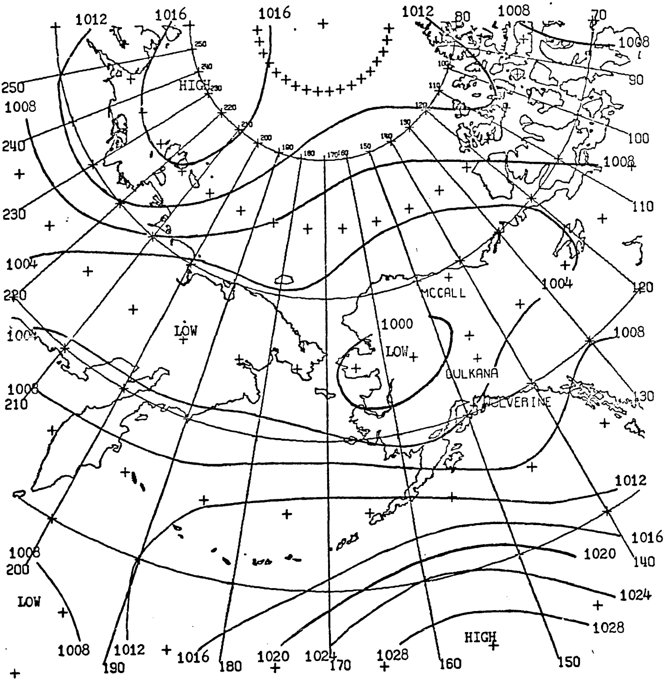

Figure D-5. Typical GS1 event: 1200 GMT 7 August 1970.

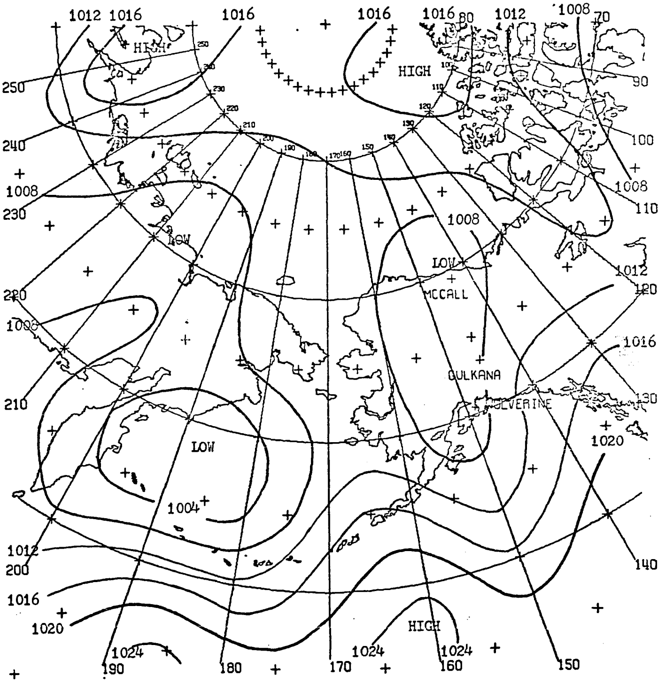

Figure D-6. Typical GS2 event—similar to MPM # 2: 1200 GMT 1 August 1970.

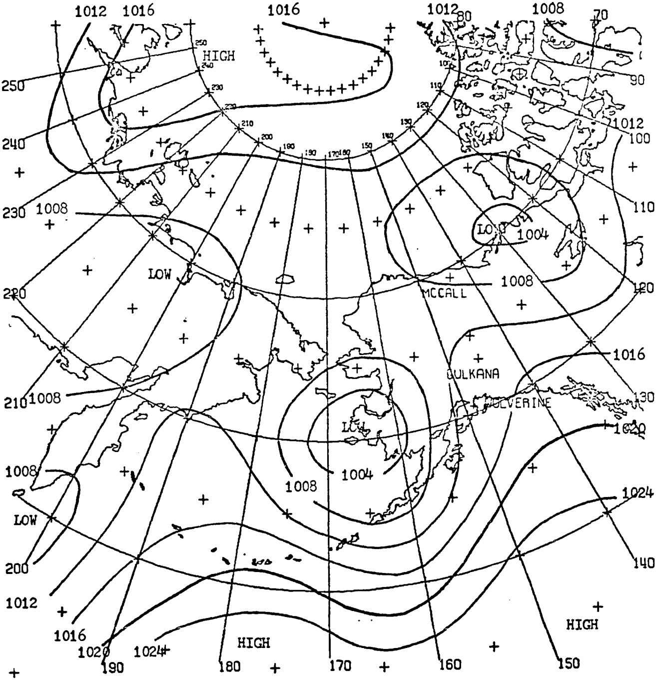

Figure D-7. Typical GS2 event—dissimilar to MPM # 2: 1200 GMT 2 August 1970.

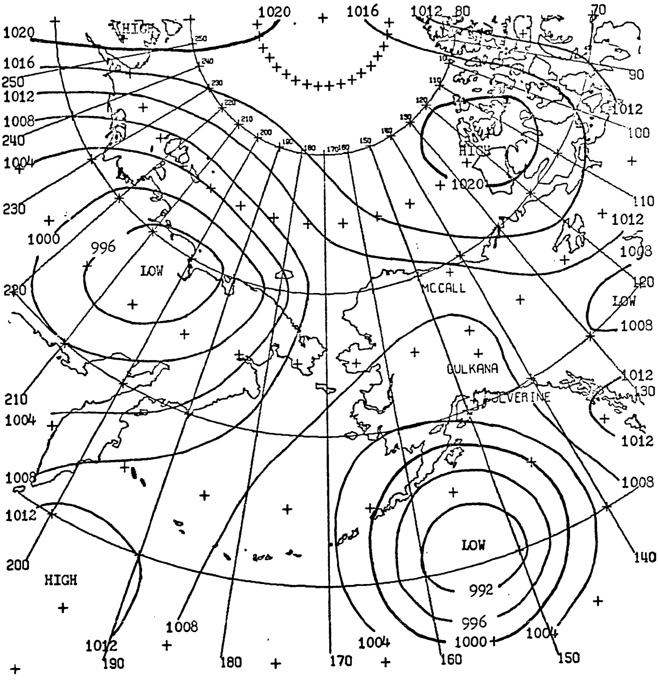

Figure D-8. Typical MH1 event: 0000 GMT 22 June 1969.

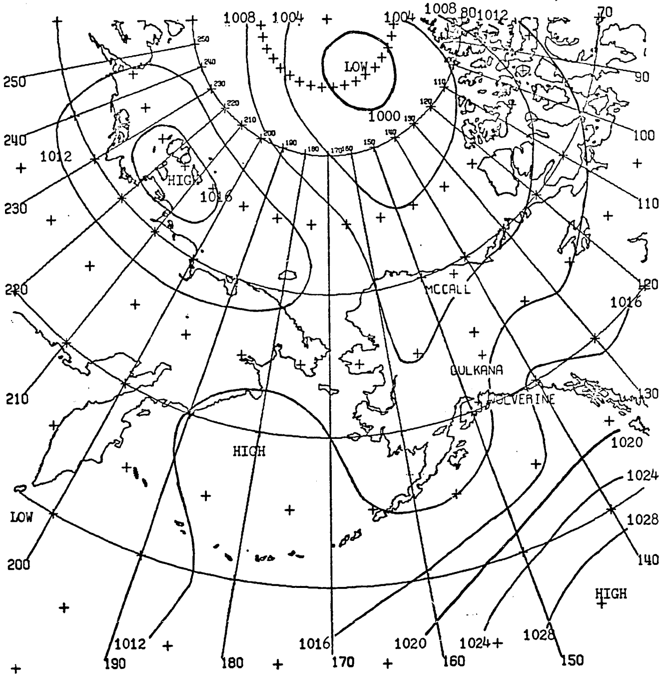

Figure D-9. Typical MH2 event—off-shore flow at McCall Glacier: 0000 GMT 6 July 1969.

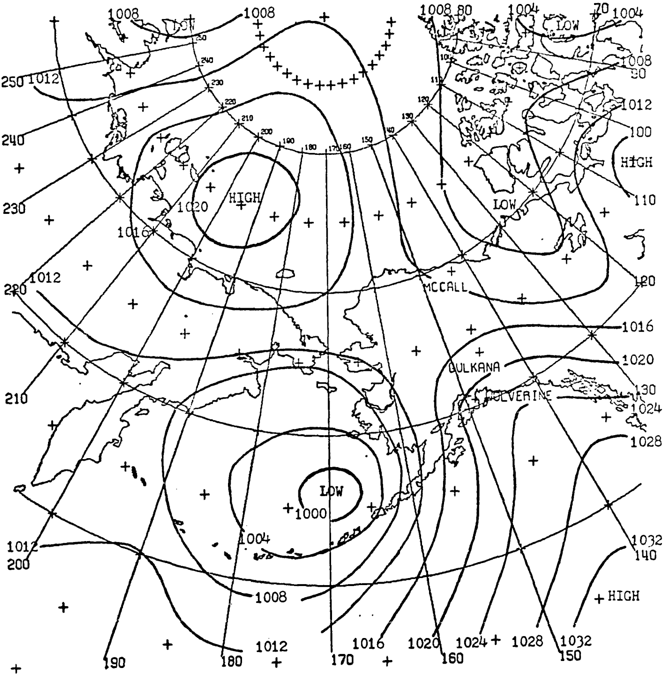

Figure D-10. Typical MH2 event—on-shore flow at McCall Glacier: 0000 GMT 19 June 1972.

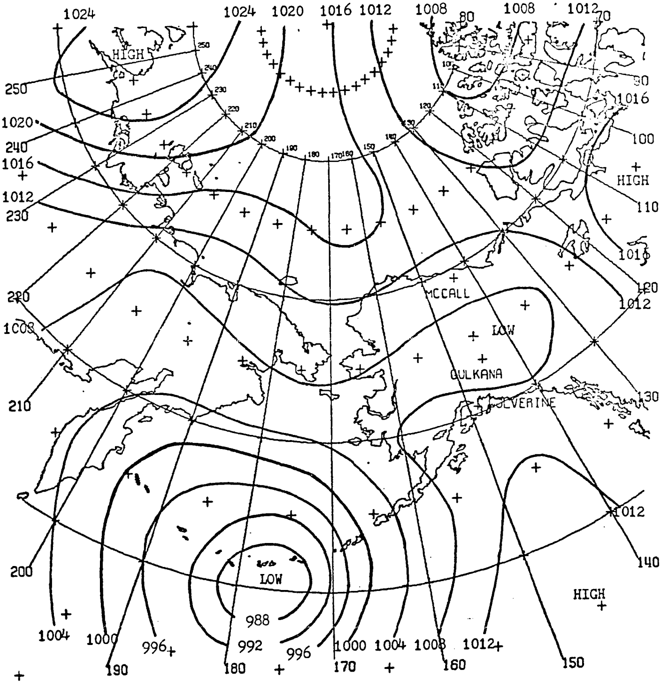

Figure D-11. Typical MH3 event: 0000 GMT 15 June 1972.

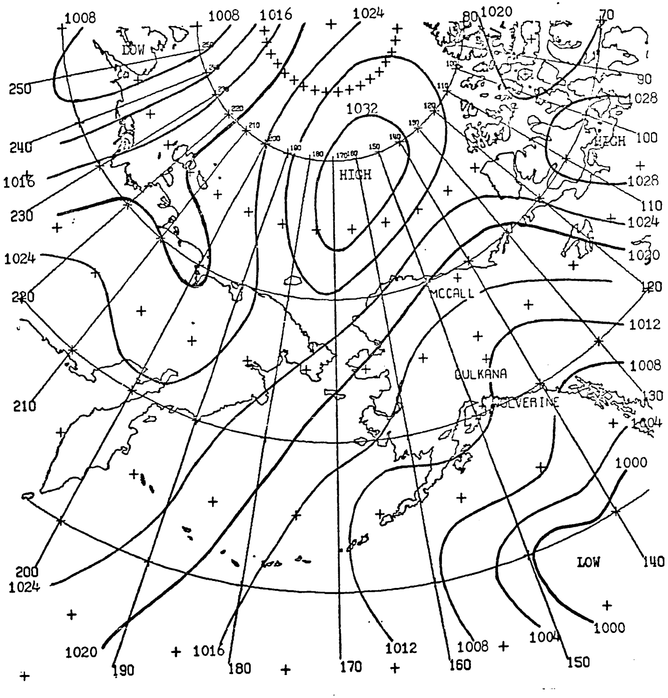

Figure D-12. Typical GH1 event: 0000 GMT 20 May 1968.

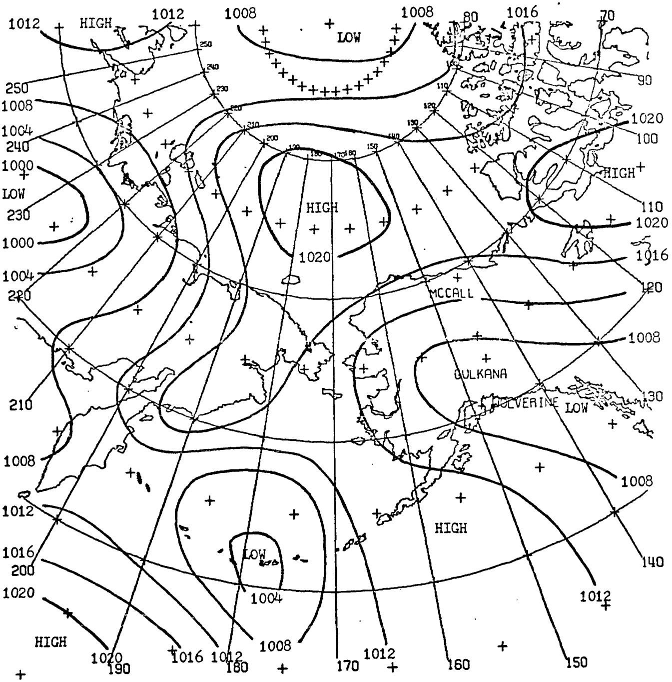

Figure D-13. Typical GH5 event: 0000 GMT 25 June 1971.

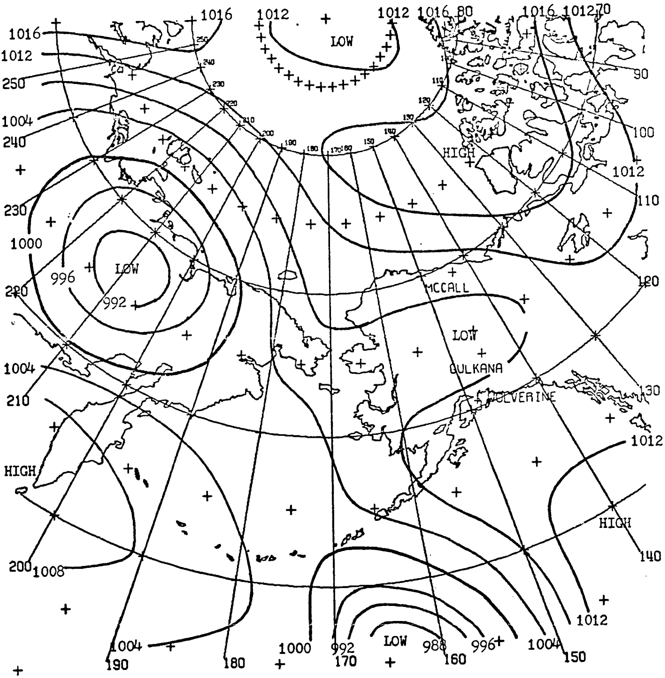

Figure D-14. Typical GH7 event: 0000 GMT 21 June 1969.

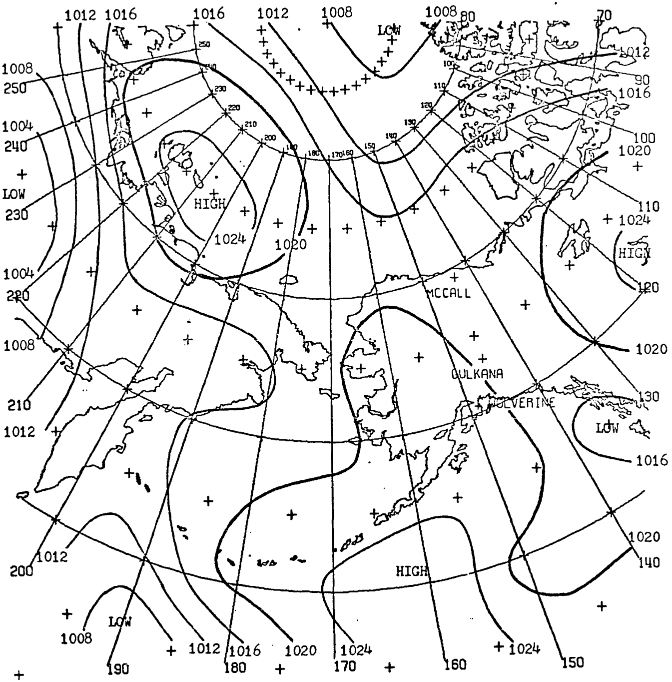

Figure D-15. Typical WH1 event: 0000 GMT 10 July 1971.

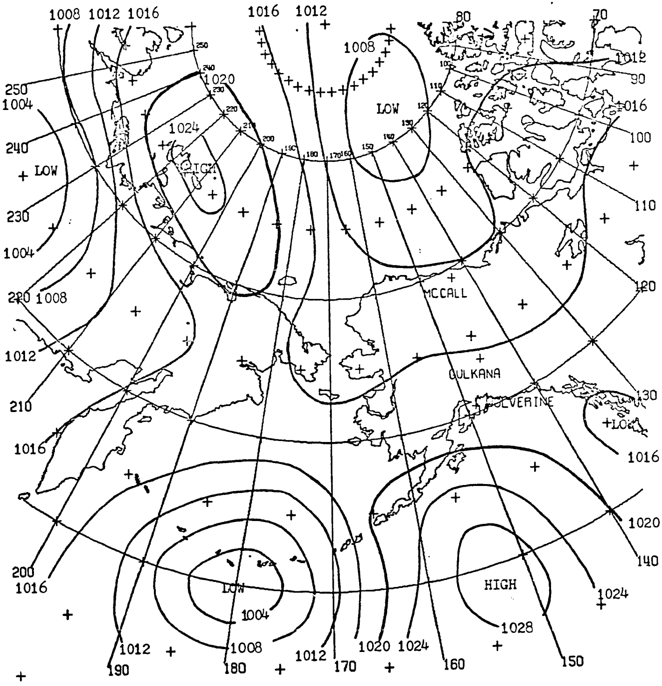

Figure D-16. Typical WH2 event: 0000 GMT 11 July 1971.

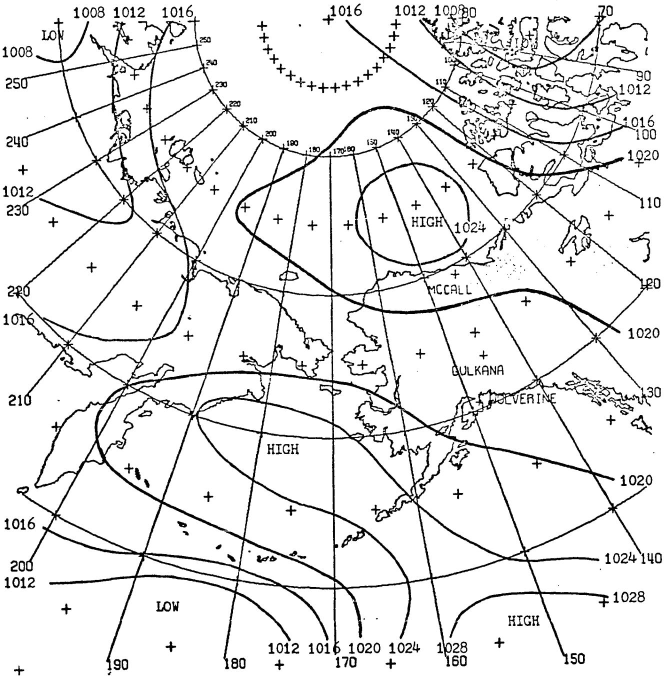

Figure D-17. Typical WH4 event: 0000 GMT 29 June 1969.

APPENDIX E

APPENDIX E

SELECTED MONTHLY MEAN PRESSURE MAPS

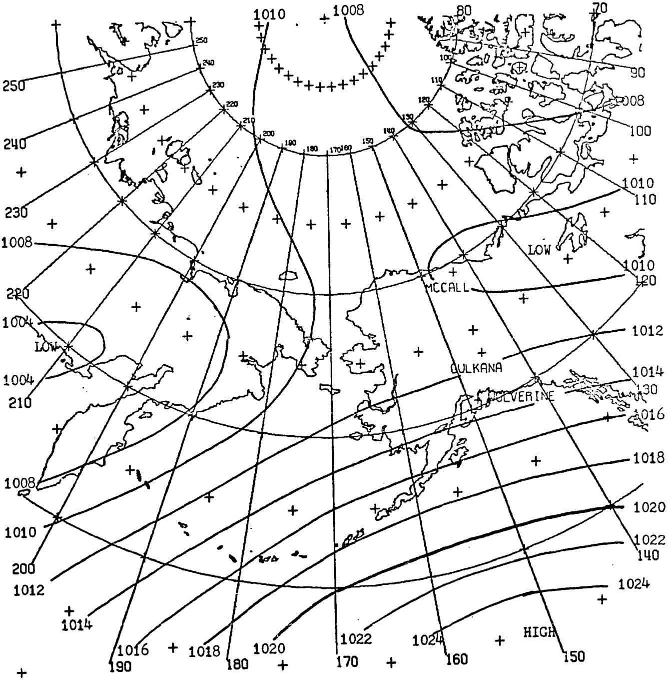

Figure E-1. Average sea level pressure (mb), July 1963.

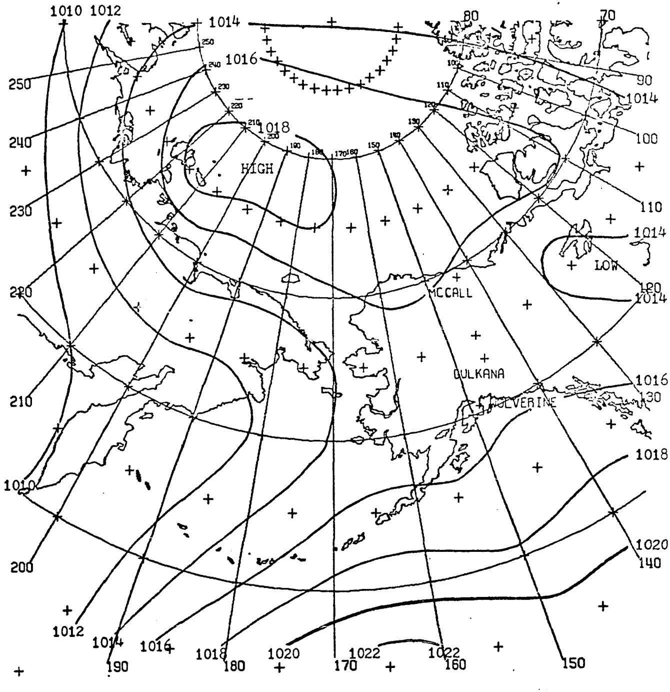

Figure E-2. Average sea level pressure (mb), July 1965.

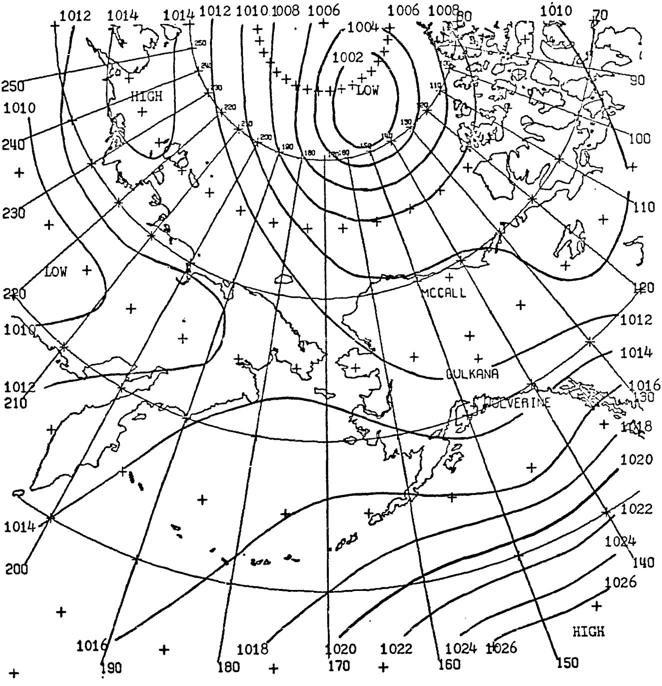

Figure E-3. Average sea level pressure (mb), July 1969.

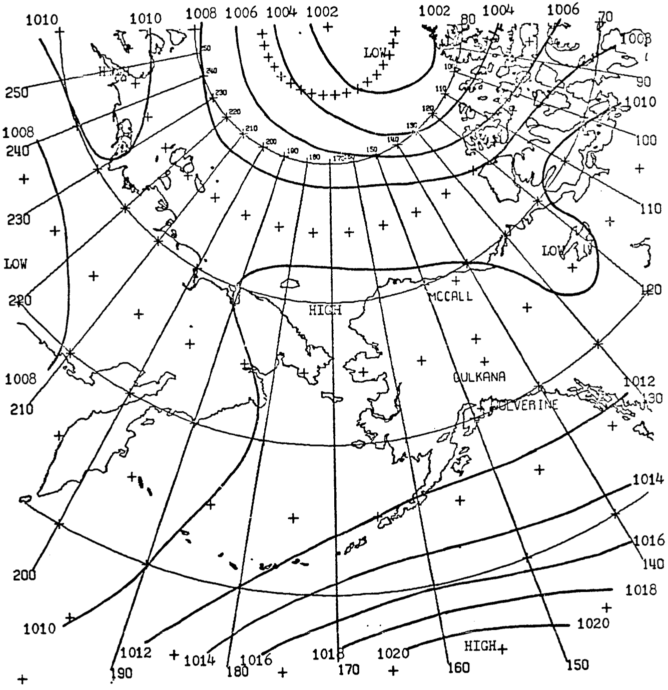

Figure E-4. Average sea level pressure (mb), July 1964.

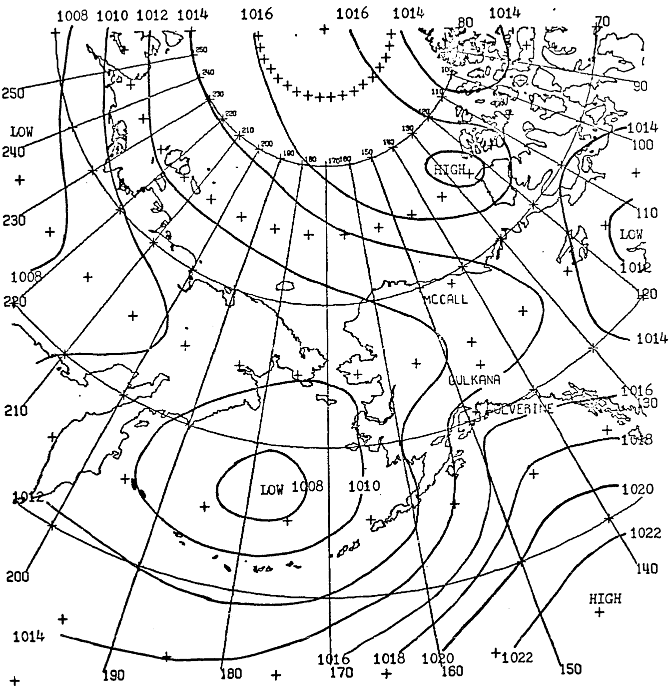

Figure E-5. Average sea level pressure (mb), June-July, 1948.

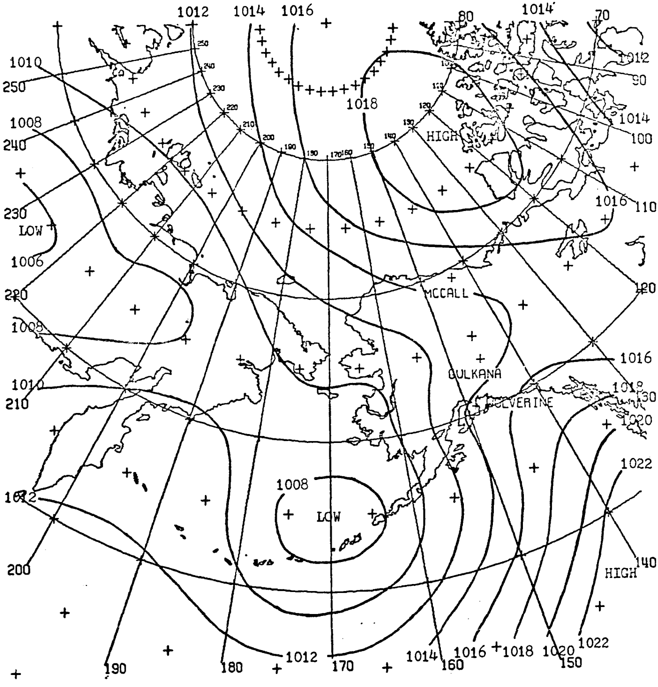

Figure E-6. Average sea level pressure (mb), June-July, 1958.

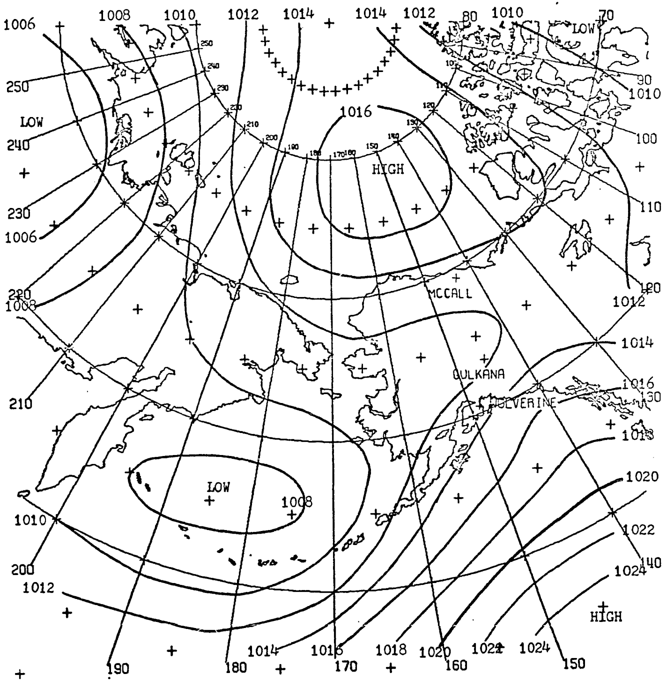

Figure E-7. Average sea level pressure (mb), June-July, 1952.

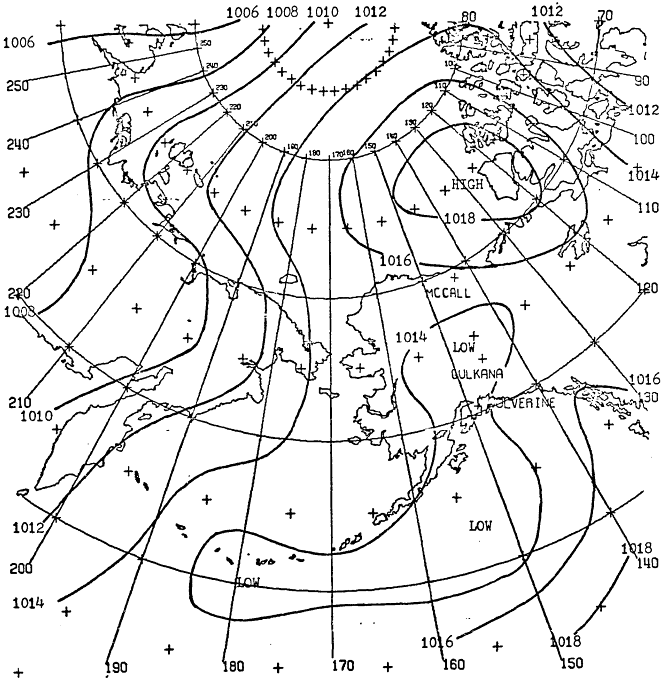

Figure E-8. Average sea level pressure (mb), June-July, 1968.

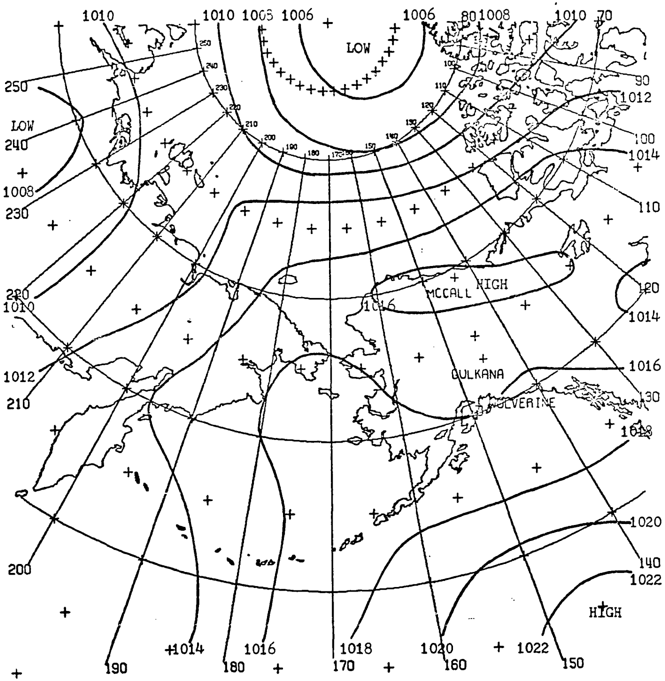

Figure E-9. Average sea level pressure (mb), June-July, 1953.

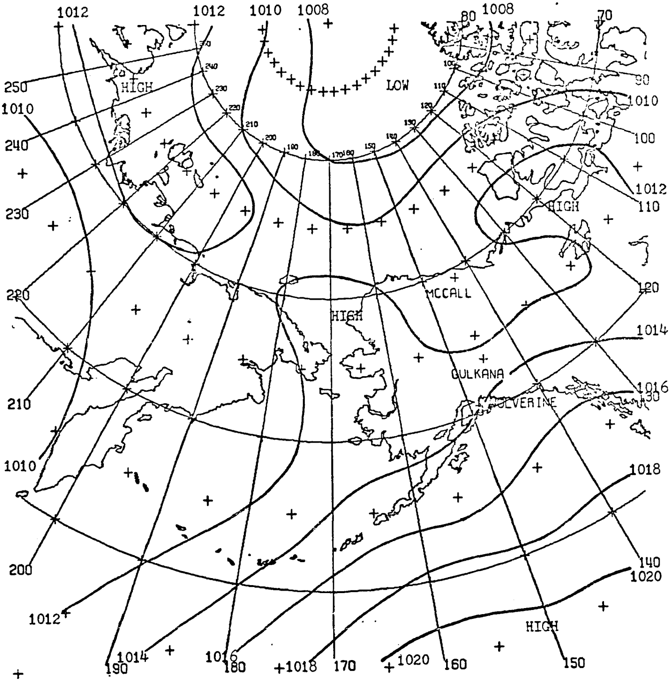

Figure E-10. Average sea level pressure (mb), June-July, 1967.