JENNIFER MARCH

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SYNOPTIC CLIMATOLOGY OF THE EASTERN BROOKS RANGE, ALASKA: A DATA LEGACY OF THE INTERNATIONAL GEOPHYSICAL YEAR

by

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SYNOPTIC CLIMATOLOGY OF THE EASTERN BROOKS RANGE, ALASKA:

A DATA LEGACY OF THE INTERNATIONAL GEOPHYSICAL YEAR

A

THESIS

Presented to the Faculty

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By

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Abstract

Abstract

Data from three International Geophysical Year (1957-1958) expeditions and one International Hydrological Decade National Science Foundation project (1969-1972) to the eastern Alaska North Slope have been rescued and made available in digital form: Chamberlain Glacier, Lake Peters, and McCall Glacier. Comparisons between these sites and US and Canadian Weather Service stations within 500km of McCall Glacier were conducted to determine the broad temperature climatology of the region. McCall Glacier is generally a swing site, and the climatology of the region often was linked most closely to the Beaufort Sea coast, though on some occasions, was more closely related to the Mackenzie River Delta and on other occasions, to the Interior. These early data represent an important addition to the Arctic data legacy by allowing a more complete climate record to be developed that focuses on a region demonstrably sensitive to climate change and yet lacking in data.

Key words: glacier, meteorology, International Geophysical Year, Alaska, McCall Glacier, Brooks Range, data rescue.

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Chapter 1: Background

1.1 Data Introduction

Development of climate time series is problematic for many areas of the Arctic due to low data densities and the short durations of time series that are available. The North Slope of Alaska occupies almost 300 000 km^2 in extent and yet is served by few weather stations, most of which are confined to the coastal zone and to the corridor represented by the Dalton Highway, constructed in 1975-1977 to service the Trans-Alaska Oil Pipeline. Prior to then, and away from that corridor and the coast, data availability is sparse. This poses significant problems for the characterization of basic regional climate patterns as well as climate trends in this region.

To augment the limited availability of observational data sets before the pipeline was constructed, data from three research field stations have been "rescued" from hardcopy archives, digitized, and made available to the research community. At two of these sites, data were originally gathered as part of the larger arctic region data gathering initiative undertaken in response to the International Geophysical Year (IGY – 1956-1959); one conducted by the Arctic Institute of North America and another conducted by the Air Force Cambridge Research Center. The third station was established as part of the research initiative surrounding the International Hydrological Decade study sponsored by the National Science Foundation and conducted by the Geophysical Institute at the University of Alaska Fairbanks. These data gathering efforts are reviewed below.

1.2 Study objectives

Much about the climate of the Eastern Brooks Range (EBR) is not well known. Thus, the broad objective of this project is to improve the climatic characterization of the EBR. Specifically, this is addressed via two focusing questions: 1) to what region is the temperature climate of the EBR most closely related; and 2) what are the major synoptic controls of temperature and precipitation on McCall Glacier? These tasks are discussed in greater detail below.

In general, addressing questions such as this is important to help establish a basis for knowing how potential changes in climate will affect the EBR. If it can be shown that the temperature climate of the EBR is similar to and linked with, say, the Mackenzie Delta, then the ongoing monitoring of the Mackenzie Delta should be able to give us clues about the trajectory of the EBR. Similarly, if broad synoptic regimes or events can be linked to snow accumulation or ablation in the EBR then changes to EBR precipitation can be inferred by understanding changes in synoptic activity, for example, such as may be prescribed by IPCC climate model projection results.

Given that much of the area lies within the Arctic National Wildlife Refuge and the Gates of the Arctic National Park, new data-gathering efforts will be strongly limited by operational policies in place in these jurisdictions, which strictly limit incursions and deployment of instrumentation. In light of these operational restrictions on future data-gathering activities, the data at hand must be employed to their fullest extent to answer climate-related questions for this area.

1.2.1 Phase I: Temperature climatology

The first task consists of categorizing the summer temperature climate of the EBR in terms of linking it into its larger climatic context; that is, is this region most similar to the Alaska Beaufort coast, the Mackenzie Delta, or the Alaska Interior. It is anticipated that the answer will not be consistent, thus a related task will be to identify the broad synoptic regimes under which the EBR is similar to different areas.

This task is made challenging by the lack of data available for the EBR. In light of this, the recovered data sets from the IGY and IHD will be fully employed to help place the EBR into a broader climatic context.

1.2.2 Phase II: Synoptic drivers of temperature and precipitation

The second task focuses more directly on the influence of specific synoptic systems to answer the question, what are the particular synoptic patterns that are responsible for accumulation and ablation on McCall Glacier. Glacier health is a function of the weather; linking McCall glacier to the large-scale weather will better enable assessment of future trends for the glaciers of the EBR.

The broad objective of this study is to determine the general synoptic controls influencing snow depth on McCall Glacier and how they have changed over time. Specific questions include:

- What is the prevalence of summer snow events?
- What does a typical storm event look like on McCall Glacier?
- How often do wind scour events, which remove snow from the glacier surface, occur?
- For the period of record, what is the frequency and magnitude of snowfall events?
- What is the main source of moisture for the glaciers of the eastern Brooks Range?
- Is there a favored direction from which storms come?
- What is the main snow depth control for McCall glacier: snowfall or wind scour?

The temporal aspect of this study will be addressed by assessing the frequency of recurrence for synoptic patterns associated with high-magnitude snow events.

1.3 History of Data and Area

In the general area around McCall Glacier and the nearby North Slope, few investigations have included the observation or analysis of meteorological data in their studies. Some, however, have incorporated significant meteorological components. Data gathered by these research efforts were applied to their original projects, and summaries of these data sets continue to appear in recent studies. The original data, however, have never been integrated in broader, regional studies, the raw observational data have never been digitized, and thus the data have not continued to be utilized. However, via a data rescue effort conducted for this study, their data have been made available. The history of scientific research on McCall Glacier is presented below, with attention focused on those studies for which meteorological data are available.

Most early investigations on McCall Glacier and vicinity were geologic in nature and were not coordinated until the initiation of the IGY (International Geophysical Year) in 1957. "The International Geophysical Year (IGY), as it was called, was modeled on the International Polar Years of 1882-1883 and 1932-1933 and was intended to allow scientists from around the world to take part in a series of coordinated observations of various geophysical phenomena. Although representatives of 46 countries originally agreed to participate in the IGY, by the close of the activity, 67 countries had become involved" (http://www.nas.edu/history/igy).

In recent years, there have not been many studies on the effects of local and large scale synoptics over glaciated areas, especially in the Arctic. Ohmura (1970) states that tundra surface conditions and sea surface conditions will affect the melting process for small- and middle-scale glaciers on Axel Heiberg Island. McCall Glacier, separated from one of its main moisture sources by a 100km swath of flat tundra, is affected by the surface conditions of both the ocean and the tundra, though the flat nature of the tundra allows for most weather systems coming from the north to reach the mountains without being slowed down or loosing much moisture.

McCall glacier is approximately 6.5km^2 in area, 6km long, and 1km at the widest point. The accumulation area lies below Mt Hubley (2718m), one of the higher mountains in the 2500-3000 m Brooks Range. From the confluence of three cirques, the glacier flows northwest for about 2km until it bends to flow north. Surface runoff in the upper cirque gathers to the northern outer edge and begins a marginal stream that continues to the toe, though it is underneath the ice at some points. Runoff from the middle and lower cirques forms a meandering surface stream at the confluence of the two cirques which then drains down a series of stepped moulin- and tunnel connections, dipping beneath the surface about 3km from the confluence, and reappearing shortly thereafter to flow along the surface until the ice ends. McCall Creek joins with the runoff from Hanging Glacier and Gooseneck Glacier, below which there is a natural weir where previous stream gauge measurements have been taken. McCall Creek flows north-northeast for 12km until it flows into the Jago River, 100km from the Arctic Ocean.

In 1957 two International Geophysical Year studies were initiated in the Romanzof Mountains of the eastern Brooks Range (Fig. 1). One, conducted by the Arctic Institute of North America, was a glacio-meteorological study situated on McCall Glacier (Mason 1959) and the other, operated by the Terrestrial Sciences Laboratory of the Geophysics Research Directorate of the Air Force Cambridge Research Center, was a lake/glacier study with sites at two locations: Mt. Chamberlin, and Lakes Peters and Schrader (Fig.1). The latter location represented a fallback field site occupied after a complication in the project forced the abandonment of the intended Ellesmere Ice Shelf study site (Holmes et al. 1959). Both studies ran for the duration of the IGY, 1956-1959. The McCall Glacier site was revisited in 1969-1971 by a team from the Geophysical Institute at UAF that continued the initial IGY studies of mass and heat balance as part of the International Hydrological Decade (Wendler 1970). Subsequent visits to McCall were also undertaken by the Geophysical Institute at UAF, which conducted studies from 1993 through 1996, collecting mass and heat balance data as well as radar depth and surface data (Rabus 1997). The most recent studies on McCall started in 2003 as part of the Freshwater Initiative project, operated by the National Science Foundation, and have been collecting data on mass and heat balances since 2003 (Nolan 2005, Klok et al. 2005, Pattyn et al. 2005). The projects from which data have been obtained for this effort are detailed below.

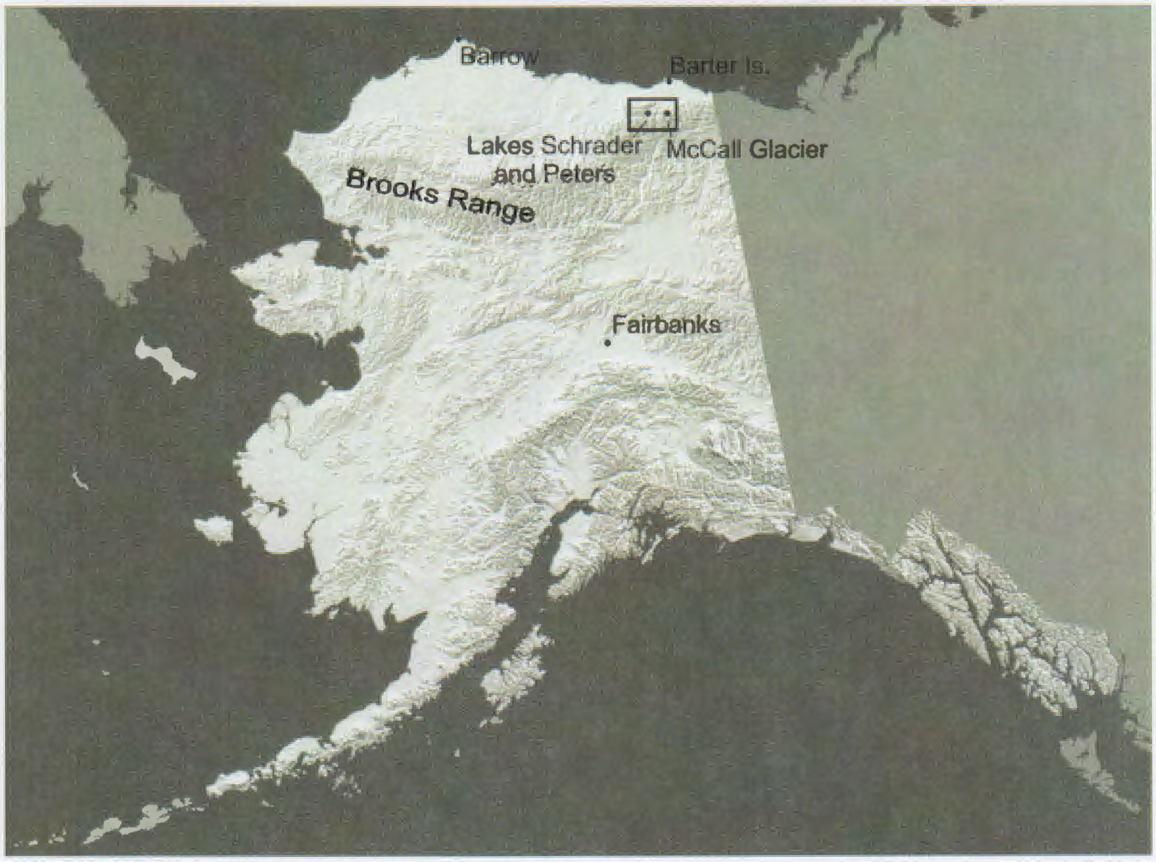


Figure 1: Map of Alaska showing the eastern Brooks Range and Romanzof Mountains.

1.3.1 1957-1958, McCall Glacier

The first IGY project on McCall Glacier established a main camp in May 1957 at the upper cirque for use as the meteorological station (parts of which are still melting out of the ice) and a lower moraine camp just below the hanging glacier (most remainders of which have recently been removed) for the surveying team (Figs. 2 and 3). "The data collected at the upper station include continuous records of long and short wave energy gain and loss, air temperatures, and wind speed. They are supplemented by regular visual weather observations and standard US Weather Bureau climatic reports" (Mason 1959).

The research team did not overwinter, thus the data collected covers the period from May-October 1957 and February-August 1958. There were no winter studies done on McCall glacier during IGY, due to the untimely death of Richard Hubley, the expedition leader.

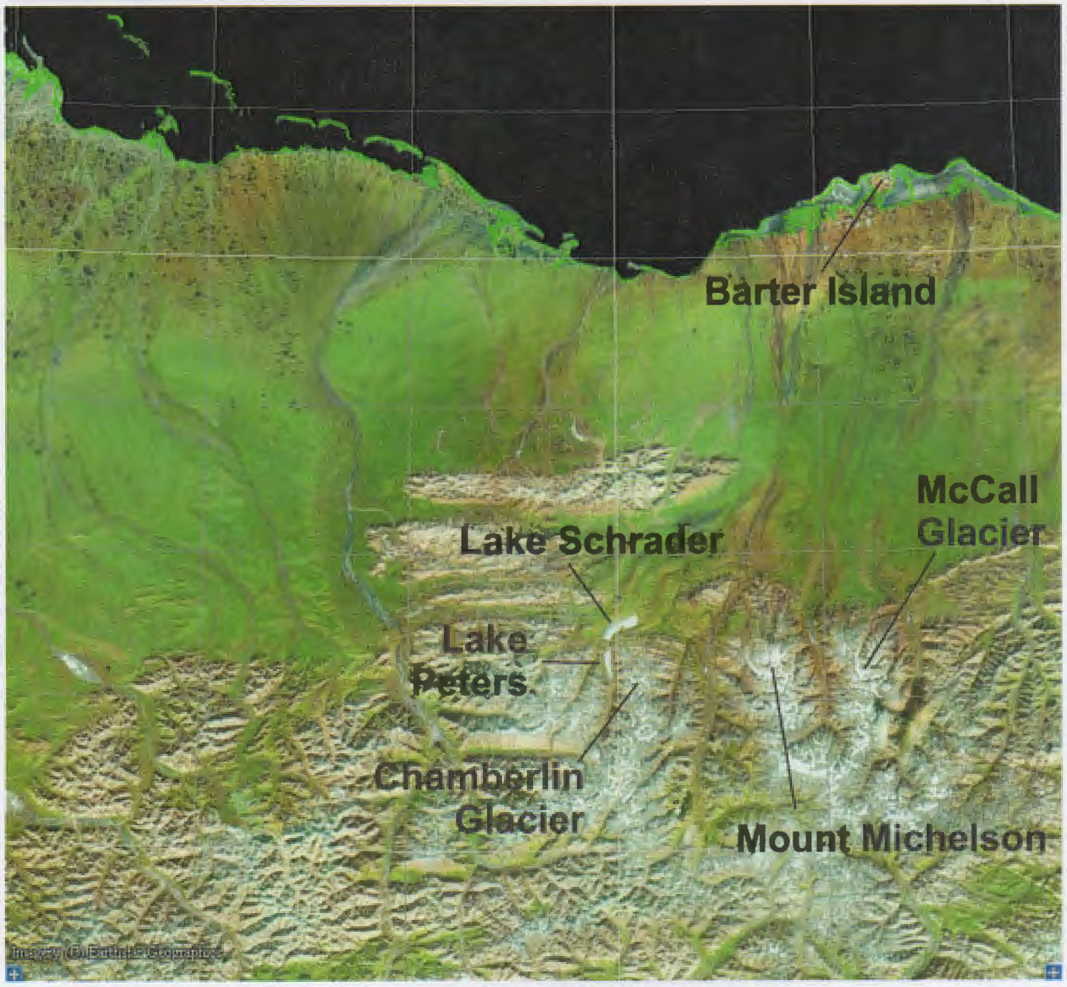


Figure 2: Map showing research areas in the northeastern Brooks Range.

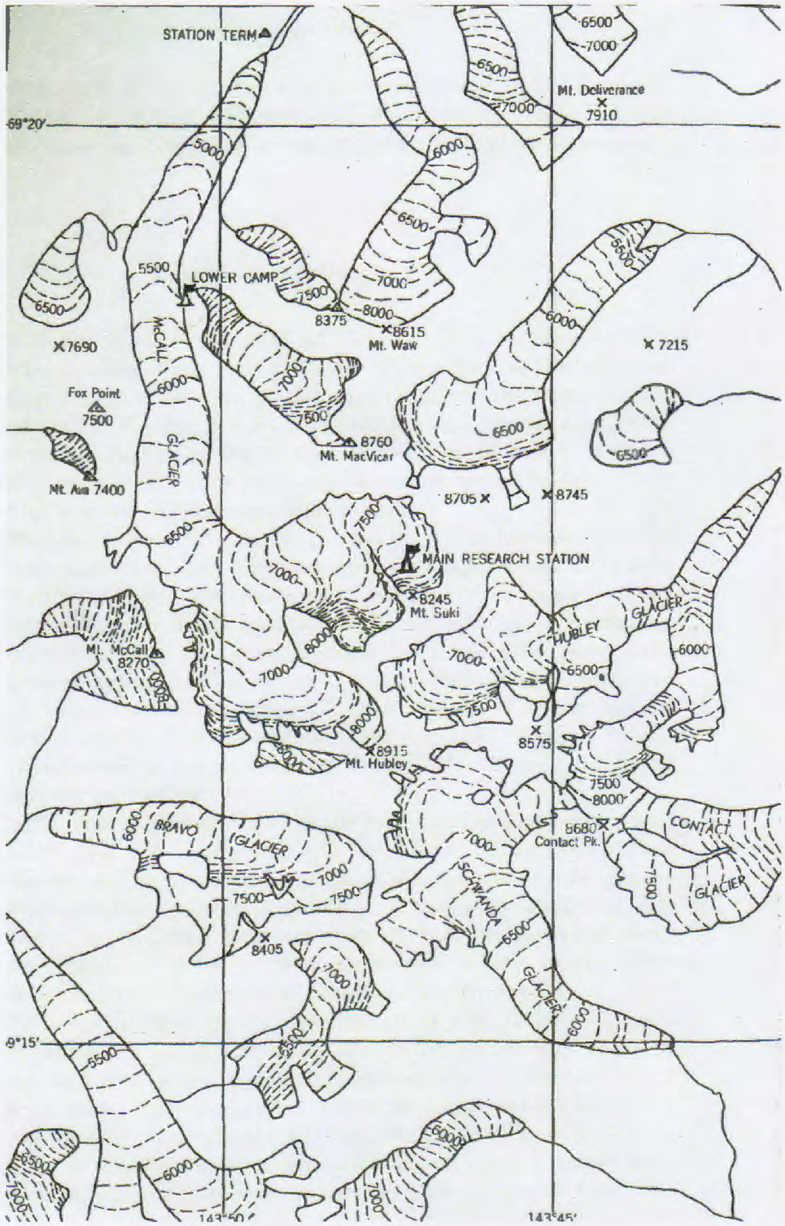


Figure 3: McCall IGY detail. (Orvig 1961)

The instruments consisted of the following (Orvig 1961, after Hubley):

- two Kipp and Zonen solarimeters
- a Beckman and Whitley net radiometer
- total hemispheric radiometer and heat flow transducer

- a Speedomax recorder
- a psychrometer
- an actinometer
- a Thornthwaite Wind Profile Register system

The complete observational record from this project is available as a published paper (Orvig 1961), in which the daily observations are typed in full and sorted by date, one day on each typed page, with columns separating each data type. These were optically scanned, translated with optical character recognition software, read into a spreadsheet, checked for errors, and reorganized.

1.3.2 1958-1961, Mt Chamberlin and Lake Peters

The second IGY project science team focused on the Mt Chamberlin area, setting up their main camp on a large alluvial fan on the shore of Lake Peters (Fig. 4) in May, 1958. The expedition was well equipped, with instrumentation at the Lake Peters site that included:

- a Thermoelectric Co. Minimite portable potentiometer
- a thermograph
- an 8-inch non-recording rain gage
- a Bendix-Friez totalizing anemometer
- an Eppley pyrheliometer
- maximum thermometer (mercury)
- minimum thermometer (mercury)

- standard thermometer (mercury)

"Temperature was recorded continuously by thermograph. The following weather elements were recorded and /or observed: global solar radiation, temperature, wet bulb temperature, wind speed and direction, sky cover and ceiling height, precipitation, visibility, and weather and obstructions to visibility." (de Percin 1959) Observations were collected from May to September of 1958; of this record only the averaged daily temperatures were ever published. The observations continue for April through August of 1959, April of 1960 through August of 1961. The full weather data set for this effort was available only as handwritten daily records on Weather Service weather log sheets, generally three days to a sheet. These were made available through inquiries to John Hobbie (one of the scientists on the team), shipped to Alaska, and transferred to digital file.

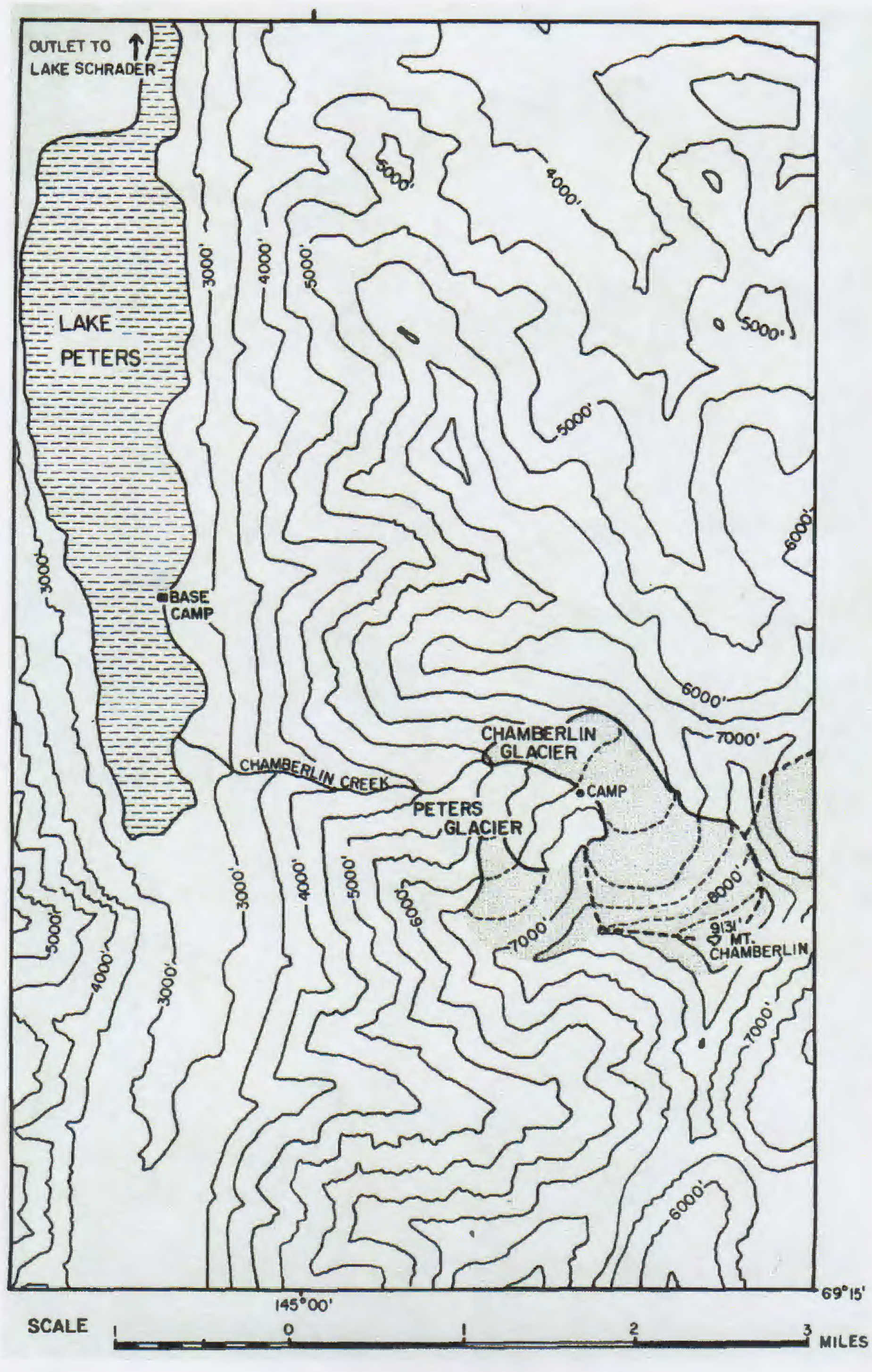


Figure 4: Mt. Chamberlin IGY primary and fly camp locations. (Larsson 1960)

The Mt. Chamberlin expedition established a secondary camp in July 1958, 2.5 miles away from and 800 feet above the primary camp, on the flanks of Chamberlin Glacier, which drains into Lake Peters. "As it was intended that a number of the natural sciences should be studied, it was necessary that the expedition should be located within a compact area exhibiting as many of the typical physical characteristics of the Brooks Range as possible" (Larsson 1960). The Chamberlin Glacier study included weather observations which were made three times daily from July through August 1958. The only record of these data are a series of published plots (Larsson 1960). A digitized set of data were manually recovered from these plots using a grid overlay.

1.3.3 1969-1972, McCall Glacier

McCall Glacier was revisited in summer, 1969. The NSF-GI team used the original IGY lower moraine camp area as their base camp, though they built a new shelter due to the collapse of the original one. Their equipment set up at the main camp included:

- Hygrothermographs
- max/min thermometers
- a Belfort actinometer
- a microbarograph
- rain gauges

Instruments were set up at other locations around the glacier at the following locations: the spine between the upper and middle cirques (the thermometer equipment is in fact still there, though no longer recording), the lower cirque (meteorology shelter still there), the terminus of the glacier, the end of the aufeis, and the moraine on which all later glacier operations have placed their base camp. The measurement program included a stream-level recorder and stream current meter placed in the outlet stream 2km below the terminus, which includes the outlet stream from the Gooseneck Glacier. "The [upper] station was established on some rocks at an elevation of 2275m on the upper part of McCall Glacier. Rauchfuss long-term recorders were utilized. The station measured air temperature, wind velocity, rock/snow interface temperature, precipitation, and global radiation" (Wendler et al. 1974). The observational data from this effort was condensed into a few graphs (Wendler et al. 1974) that are monthly or yearly averages compared with averages for Fairbanks and Barter Island, except for the summer of 1969, which has temperature data graphed in full (Wendler 1970). The daily data from the terminus are published in graph format in the 1970 paper Studies on the McCall Glacier. Data were extracted from these graphs and digitized.

1.3.4 1980's, McCall Glacier

Little work was conducted on the glacier in the 1980's, though a short reconnaissance mission was flown to pick up some equipment, weather stations were checked on, and the glacier was overflown a few times. The data from this era is on paper tape, and was unavailable for this study. (Echelmeyer, Harrison, and Benson, personal communication)

1.3.5 1993-1996, McCall Glacier

A team from UAF-GI established a new main camp location on the moraine to the north of the confluence (where all camps have been based since) and took meteorological and mass balance measurements. The temperature data from May through September of 1994 is available as a graph in Rabus (1997). The graph was scanned and the data digitized.

1.3.6 2003-2008, McCall Glacier

The most recent effort on McCall Glacier reoccupied the moraine site and employs essentially the same observational regime as used in previous efforts, though some of the instrumentation has changed. Automated weather stations have made available a longer continuous record that extends over winter with higher frequency observations, though margin for error increases as a lack of human intervention means they are not checked and can encounter problems such as accumulation of rime ice or hoar frost, which can adversely affect anemometer calibration or decrease temperature response sensitivity, for example. Weather stations have been set up near the old lower moraine camp (below the hanging glacier), one placed in the upper cirque, one on a high point on Mt Ahab (to the north above the new moraine camp), and one near the terminus (Fig. 5).

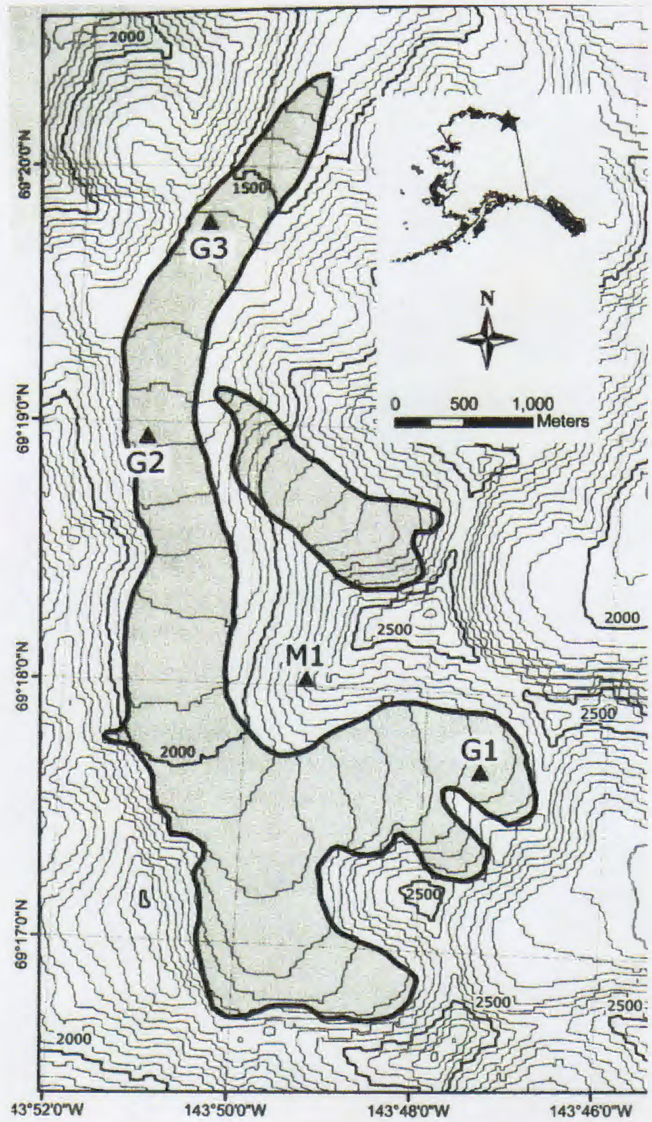


Figure 5: McCall Glacier modern station distribution (Weller et al. 2007)

Some of the equipment has included thermometers, sonic height ranger, wind speed and direction sensors, radiation sensors, and data loggers. (Klok et al. 2005) These data were made available as an Excel spreadsheet by Nolan. Weather records for other areas of the North Slope, including Barrow and Barter Island, is collected by the National

Weather Service and archived at the National Climatic Data Center (both divisions of NOAA), and are available in electronic form.

Chapter 2 Methods

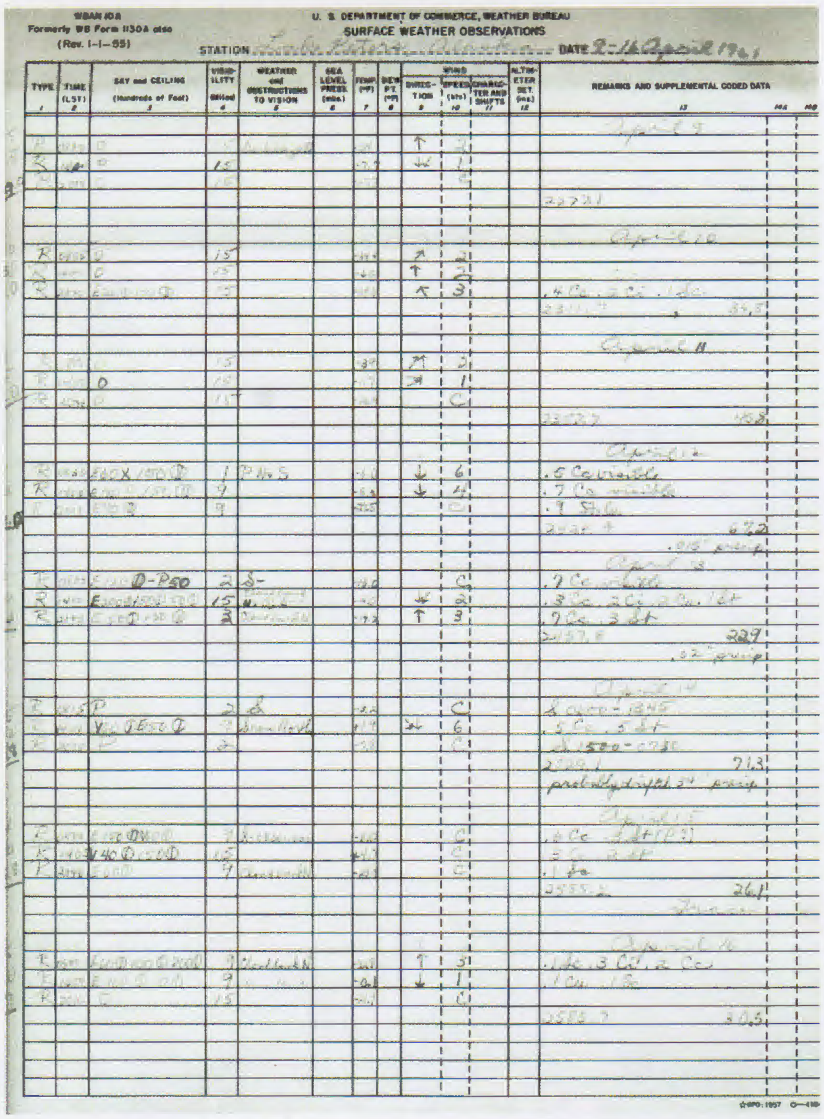
2.1 Data

2.1.1 Rescued data

McCall Glacier was first studied in 1957, when an IGY group set up camp on the glacier in June, staying until the end of October of 1957, and returning in April to continue studies until the middle of August 1958. In July of 1958, another IGY group initiated study of the area adjacent to Lakes Peters and Schrader. This group also collected weather data, and spent July and August exploring the scientific possibilities of the area, including studies on Chamberlin Glacier. This group returned in 1959 from April through August, and again in 1960, this time over-wintering at the site and collecting data until August of 1961. The next set of available data is the next study done on McCall Glacier, from June to August of 1969, and picking up again for June and July of 1971. This study was part of the International Hydrological Decade (IHD), with the scientists coming from the Geophysical Institute (GI) at the University of Alaska Fairbanks (UAF). There was another GI study performed in 1994, from May through September. The IGY McCall study has printed weather observation records (Orvig 1961) which are typed in full and sorted by date, with one day per page and columns separating each data type. These data were scanned, translated by optical character recognition software, read into a spreadsheet and checked. The Chamberlin Glacier data were published in a thrice-daily observation graph (Larsson 1960). This graph was scanned and digitally analyzed with a grid overlay to create a spreadsheet. The Lake Peters data were presented as handwritten weather observation sheets with three to eight observations per day. These data were made available and sent to Alaska by John Hobbie (a member of the science team), and transferred to digital file. The weather records from the interim period between IGY and the current study are available in graph form in various publications (Wendler 1970, Wendler et al. 1974, Rabus 1997).

2.1.1.1 Documents scan

Some of the data were available only in tabular appendix form in reports or as original field notes (Hobbie, pers. comm.). In these cases data were scanned.


WBAN 10A
Formerly WB Form 1130A also
(Rev. 1-1-55)

U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU
SURFACE WEATHER OBSERVATIONS

STATION Lake Peters, Alaska DATE 9-16 April 1961

TYPE 1	TIME (LST) 2	SKY and CEILING (Hundreds of Feet) 3	VISIBILITY (Miles) 4	WEATHER and OBSTRUCTIONS TO VISION 5	SEA LEVEL PRESS. (mbs.) 6	TEMP. (°F) 7	DEW PT. (°F) 8	WIND DIRECTION 9	WIND SPEED (kts) 10	WIND CHARACTER AND SHIFTS 11	ALTIMETER SET. (ins.) 12	REMARKS AND SUPPLEMENTAL CODED DATA 13	14A	14B

Figure 6: Sample of Lake Peters observations, April 9-16, 1961 (Copy of original)

2.1.1.2 Grid overlay

In a few cases, data were available only in reduced form on a plot. In these cases a fine grid overlay was set down and data reconstructed from the grid/plot intersections.

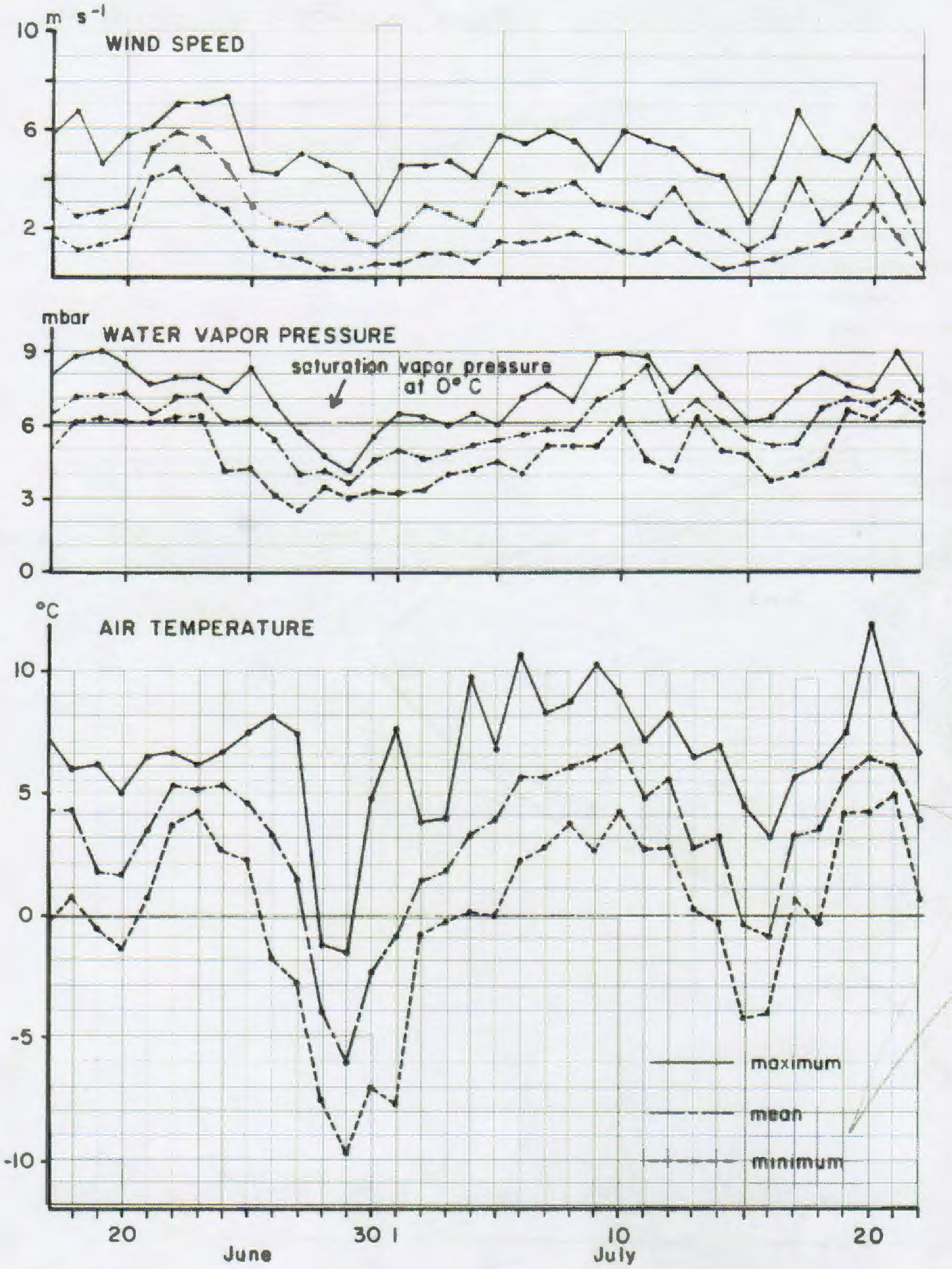


Figure 7: Example of a grid overlay to extract data points, June 17- July 22, 1971 (Copy of original)

2.1.2 McCall Glacier data

Glaciological studies on McCall Glacier have been ongoing from May 2003 to the present, with data available to this project through August 2005. Two weather stations are in operation, AHAB and JJMC. AHAB is on the top of the peak to the north of the glacier's curve, and JJMC is located in the middle of the glacier valley, near the tongue of the Hanging Glacier.

Table 1: McCall Glacier weather data gathered

Station	Elevation	Parameters
AHAB	3000m	Solar panel temperature 3m air temperature 3m relative humidity 1m air temperature 1m relative humidity wind speed wind direction maximum wind speed precipitation
JJMC	1500m	Log temperature 3m air temperature 3m relative humidity 2m air temperature 2m relative humidity 1m air temperature 1m relative humidity 3m wind speed 3m maximum wind speed 1m wind speed 1m wind direction 1m maximum wind speed sonic ranger distance precipitation

2.1.3 Regional Weather Service station data

Data from Barrow and Barter Island, as well as other North Slope (and interior) weather stations, is from NOAA's National Climatic Data Center. Station data from Canadian stations are from Environment Canada. Other weather stations include Hershel Island, Ivvavik, Komakuk Beach, Margaret Lake, Old Crow, Shingle Point, Aklavik, Inuvik, Pelly Island, Tuktoyaktuk, Liverpool Bay, Storm Hills, Trail Valley, Anaktuvuk Pass, Arctic Village, Canyon Village, Chalkyitsik, Chandalar Lake, Chandalar Shelf, Coldfoot, Colleen River, Colville Village, Deadhorse, Dietrich Camp, Fort Yukon, Franklin Bluff, Galbraith, Happy Valley, Killik, Kuparuk, Lonely, Toolik Lake, Prudhoe Bay, Sagavanirktok River, Umiat, Venetie, Wild Lake, Wiseman, Oliktok, and Nuiqsut.

2.1.4 Reanalysis data

Plots of synoptic overviews were generated using the NOAA CDC website with data based on the NCEP/NCAR Reanalysis.

2.2 Phase I methods: Temperature climatology analysis methods

Determining how these stations in fit into the context of the regional-scale climate patterns was performed in the following manner. First general IGY site data summaries using all available parameters are presented. Second, using these stations, the region of the eastern Brooks Range is fit into its regional climatic context using correlation and cluster analyses with stations within 500km of McCall Glacier. Details of the correlation and cluster analysis methodologies are presented below. Finally, the different patterns emergent in the analysis results were placed into their synoptic context using mean patterns of geopotential height to indicate major atmospheric flow regimes. Details of the synoptic methodology are also presented below. In all cases analyses were broken down into time periods that would maximize use of some of the shorter period IGY stations. Often this precludes the use of the climatological standard summer season.

2.2.1 Regional weather reporting sites

Daily temperature data from all reporting weather stations held at NOAA's National Climatic Data Center that were situated within 500km of McCall Glacier were obtained for the climatic context study. All data (except for Nolan data 2003-2005) used in this project – rescued IGY data and data obtained from NOAA – are provided on the accompanying data CD (Appendix 3).

2.2.2 Data Summaries

Simple time series of all data parameters for the IGY sites were constructed. This allowed ready assessment of trends and broad patterns during the periods of record, facilitating the synoptic context analysis, and it showed how the stations differed from one another in terms of elevation effects on temperature.

2.2.3 Development of regional station groupings

Two sets of cluster and correlation analyses were conducted. First, analyses were conducted for the time periods when the IGY sites were in place and for other times when data were available at these locations. This allowed the sites to be linked to longer-term weather stations they most closely match. The second set of cluster analyses examined each year, broken down by season, in order to identify the larger-scale spatial patterns. The combination of these two analyses allowed McCall Glacier, Lake Peters, and Chamberlin Glacier to be identified with their typical climatic region, e.g., interior, Beaufort Coast, etc., because the research sites are tied to longer-term stations that are in turn tied to climatic regions.

2.3 Phase II methods: Synoptic analysis methods

2.3.1 Definition of Seasons

Many climatic parameters exhibit a seasonal dependence. Often studies of processes that involve a climatic dependency move beyond reference to annual means to consider seasonal variations, recognizing that the process under consideration might vary considerably from one season to the next. Often a calendar system is used to define seasons, in which each season is an equal three months in length. This tends to be a mid-latitude approach. In the arctic this definition does not work as well because the summer is short and the shoulder or transition seasons (autumn and spring) are very short, that is, with reference to the mid-latitude source of the three-month system. For this reason the seasons on McCall Glacier are defined for this paper as follows:

Summer: June – August

Autumn: September (average temp -10° C for 2003-2005)

Winter: October – April

Spring: May (average temp between -6° C and 1° C for 2003-2005)

This definition is based on a visual inspection of the mean daily temperature curve averaged over several years (Fig. 10). This definition will be used whenever analyses are broken down into the seasonal level.

2.3.2 Definition of a storm

The identification of storms and other weather events likely to impact the glacier was conducted by visual inspection of the time series from the McCall Glacier stations. Events were identified based on the occurrences of strong winds and/or heavy precipitation, or high temperatures. To then determine the nature of the air masses affecting McCall during these events, broad synoptic overviews were obtained using plots of 700hPa circulation generated at the NOAA Climate Data Center (CDC) interactive daily composite plots website (http://www.cdc.noaa.gov/Composites/Day/). The 700hPa level was selected at that closest to the level at which the McCall sensors are positioned. Finally, to place the synoptic regime into its seasonal context, these patterns were contrasted with weekly averages taken before and after the event.

To place the detailed synoptic results into the broader context of atmospheric flow patterns, and to allow comparison between time periods during which McCall Glacier data were gathered (2002-2004) and earlier periods, monthly and seasonal average composite plots were generated for the McCall area for all time periods for which any data were available. These plots were averaged to obtain the mean pressure pattern and the typical variability. In this way annual patterns could be assessed with respect to their degree of anomaly.

2.3.3 NOAA Climate Diagnostics Center analysis tool

Data and a graphical summary tool to perform analyses of upper air flow patterns were obtained from NOAA's Earth Systems Research Laboratory at this website: <http://www.cdc.noaa.gov/cgi-bin/data/getpage.pl>

Analyses consisted of composites (means) of 850 mb (~3000m elevation) geopotential height corresponding to varying periods that match the time frames under consideration.

Chapter 3 Results

3.1 Data availability

3.1.1 Rescued IGY and IHD data

Several thousand data points have been made available via the data rescue process. A broad summary is provided in Table 2. Data for the IGY sites were recovered from the available sources listed above in a digitization and quality control process. Data totals by type and location are presented in Table 3.

Table 2: Summary of data available from McCall Glacier, Chamberlin Glacier, and Lake Peters during the International Geophysical Year expeditions.

Site	Total observations	Dates	Parameters
McCall Glacier	28,665	6/13/1957-10/31/1957 3/1/1958-8/18/1958 6/22/1969-8/2/1969 6/17/1971-7/22/1971 5/25/2003-8/25/2005	Temperature Precipitation Relative Humidity Wind Speed/direction Cloud Cover Albedo
Chamberlin Glacier	61	7/1/1958-8/31/1958	Temperature Relative Humidity Rain and Snow Ablation Stream Discharge
Lake Peters	2297	7/12/1958-8/27/1958 4/29/1959-8/28/1959 4/19/1960-8/31/1961	Temperature Precipitation Weather/visibility Wind Speed/direction Relative Humidity

3.1.2 Other data availability

Summaries for temperature, wind, and precipitation data are presented for the research sites at McCall Glacier, Lake Peters, and Chamberlin Glacier for all periods they are available.

Table 3: Weather data availability over the eastern North Slope. Barrow and Barter Records are continuous for this period.

Year	McCall	Chamberlin	Peters	Barrow	Barter	Deadhorse	Kuparuk	Umiat	Wainwright
1958	x	x	x	X	x				
1959	x	x	x	X	x				
1960			X	X	X				
1961			X	X	X				
1969	x			X	x				
1970	x			X	x				
1971	x			X	x				
1991	x			X	x	x	x	x	x
1992	x			X	x	x	x	x	x
1993	x			X	x	x	x	x	x
2003	x			X	x	x	x	few	x
2004	x			X	x	x	x	few	x
2005	X			X	x	x	x	few	x

Barrow and Barter Island are listed in Table 3 above, however, to better place these data into regional context comparisons between the research sites and weather station records for all US and Canadian Weather Service stations within 500km of the McCall Glacier location (Fig. 8).

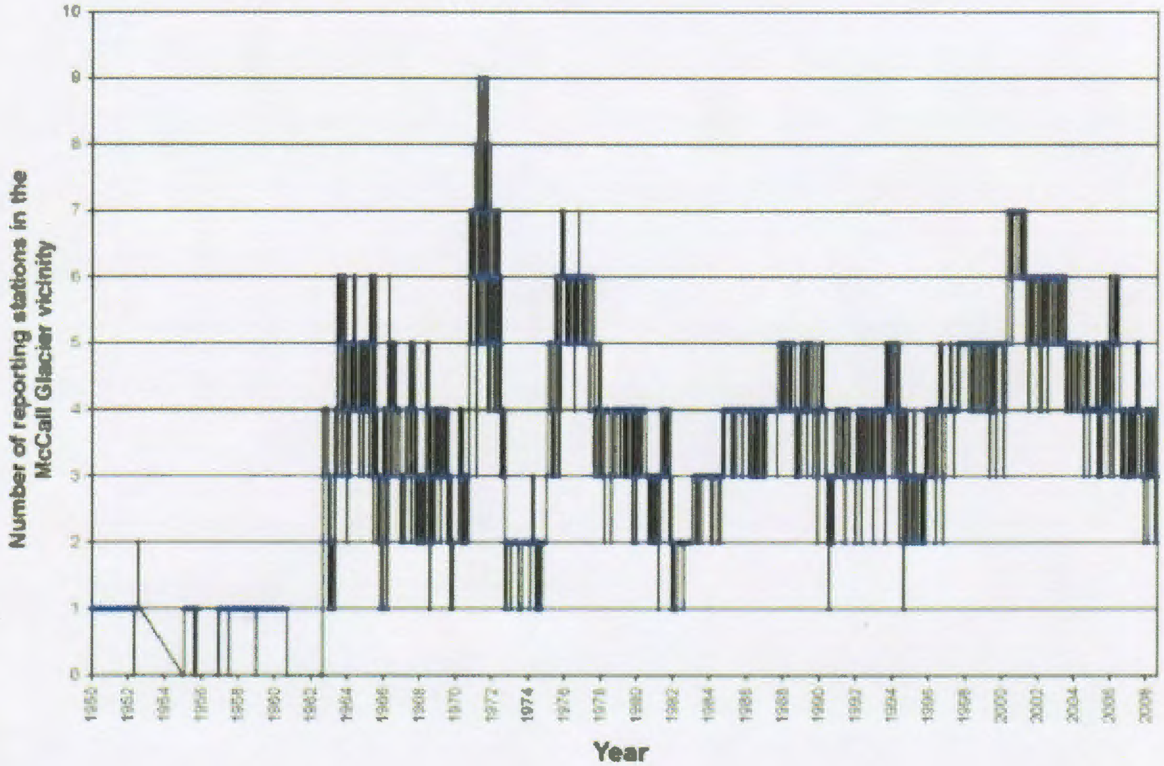


Figure 8: Active weather station counts for 500km radius around McCall Glacier, by month, by year. US and Canadian Weather Service stations included.

National Weather Service stations situated on the coast at Barrow and Barter Island are focused on because they have the longest records. At the research sites most of the weather data time series are limited to the summer season, due to the relative logistical ease of gathering data. Summer is defined here according to the climatological standard as encompassing the months of June, July, and August. Where the season must be truncated it is indicated. Weather station data were obtained from the archives at NOAA's National Climatic Data Center.

3.2 Temperature

The coastal weather stations possessed similar mean summer temperature values that fluctuated around 2.5-3° C until the mid 1980s when a weak upward trend commenced (Fig. 9). Interannual temperature variability was present that caused actual temperature values to range between 1.5 and 5 with several higher peaks after 1990. In general, the two coastal sites varied in phase with a few exceptions (1957, 1980-1984). Interannual variability appears to have increased after the upward trend began. Research station average summer temperatures reflected their elevation and their distance from the coast (Fig. 10). Lake Peters was lowest elevation and exhibited the warmest summer temperatures, McCall station's elevation and proximity to the glacier gave it means comparable to the coast, and the single seasonal datum for Chamberlain Glacier places it between these two. Where it could be observed, the interior stations possessed indications of greater inter-annual variability than those on the coast, an expected result for sites removed from maritime stabilizing influence.

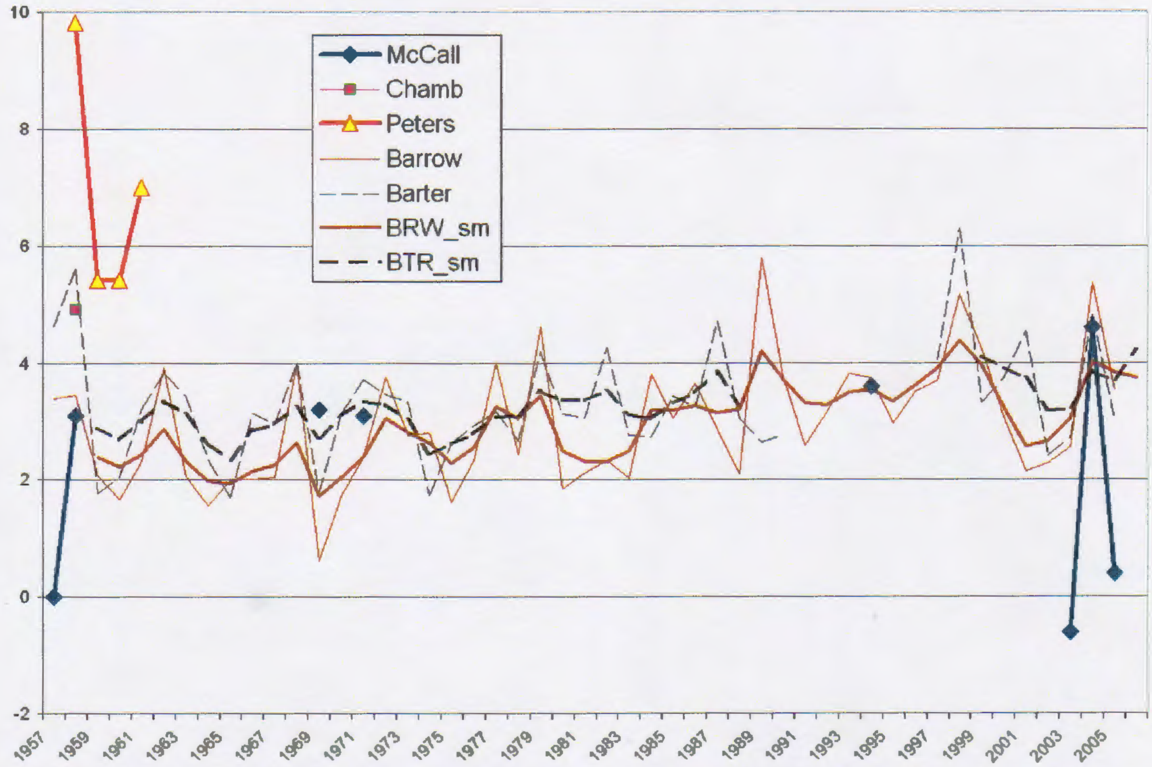


Figure 9: Barrow, Barter, Peters, Chamberlin, and McCall data time series, 1957-2005

Inclusion of weather station data helps to put the research station observations into context (Fig. 11). 1958 emerges as a very warm summer in the eastern part of the region – Barrow, west of this area, does not echo the strength of the warm anomaly. For Barter, however, it is the second warmest summer in the 1957 – 2005 record. Lake Peters and McCall Glacier stations reflect this; Lake Peters further echoes the two cool years in 1959 and 1960 and a warmer 1961. The station data also indicate a warming from the mid 1970s to the mid/late 1990s. McCall also reflects the strong peak in 2004 seen in the weather service stations, although the relative magnitude of the peak is greater at McCall. Further contrasting McCall results with the coastal stations suggests that, when McCall is warm the North Slope is warm, however when McCall is cool it is a more localized effect

– the coastal sites are not as cold as McCall. This will also be a byproduct of their coastal situation.

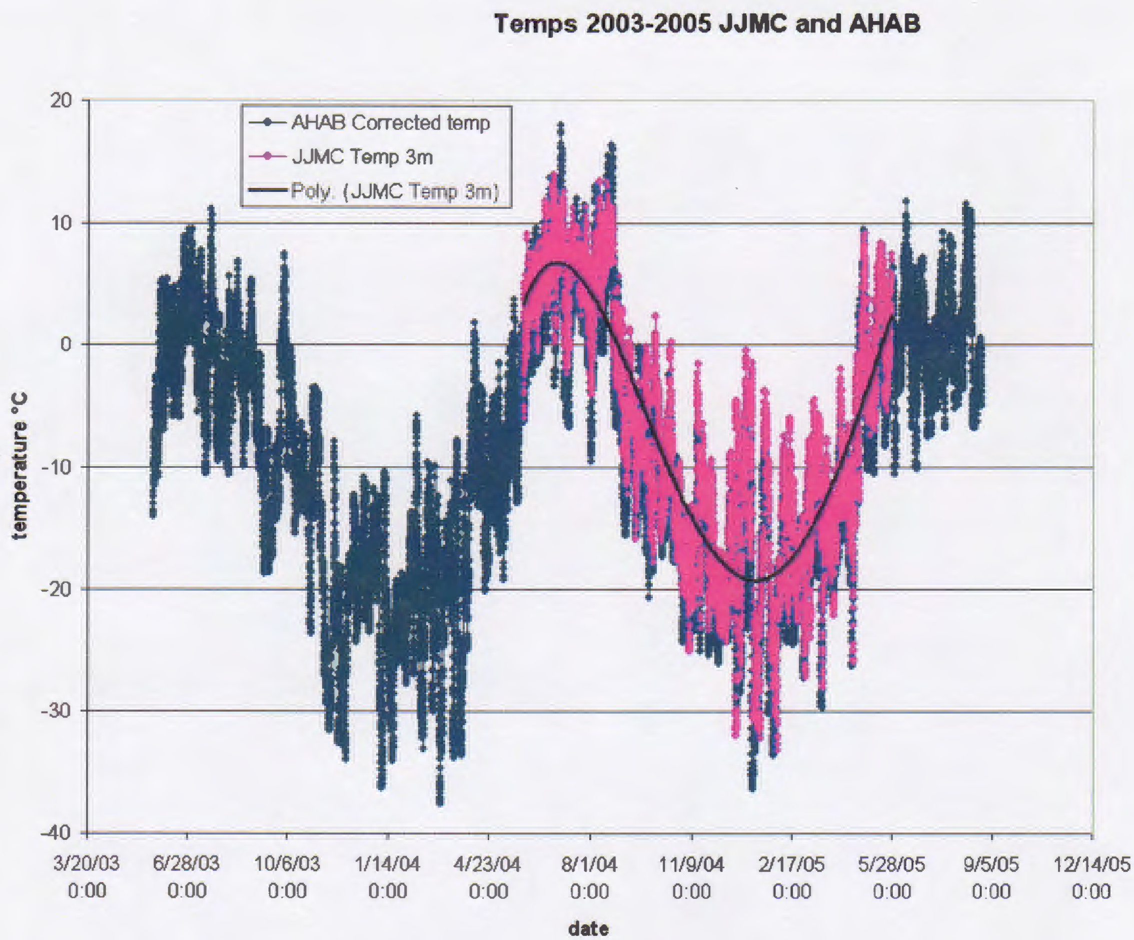
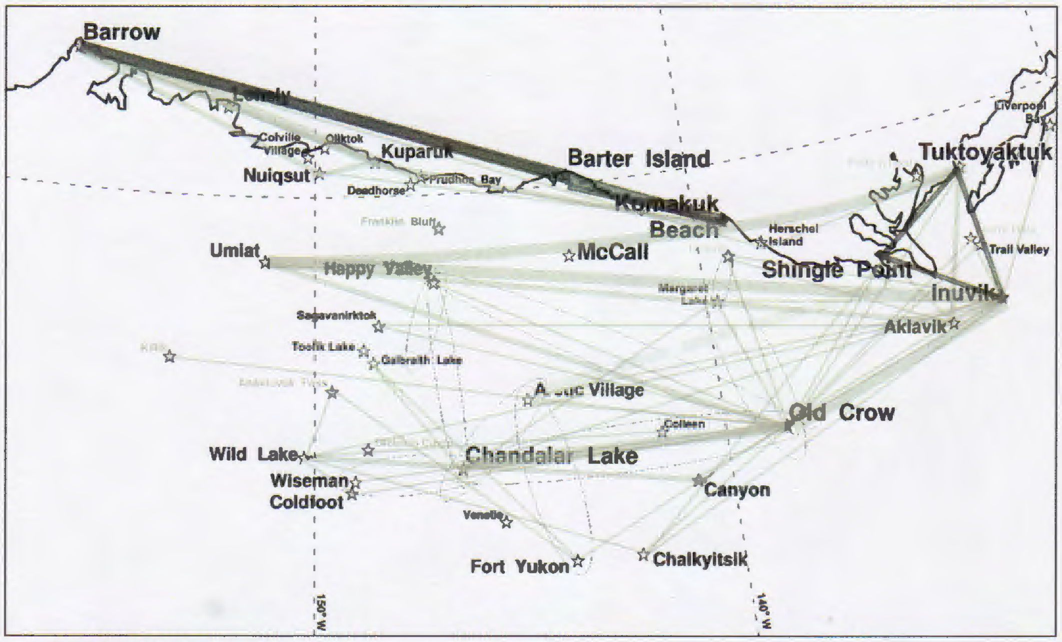


Figure 10: Mean daily temperatures averaged between McCall Glacier stations JJMC and AHAB, averaged over the years 2003-2005.



Preliminary scheme:
Full size - present for 25+ of 1960 - 2005
80% size - present for 5 - 24
50% size - present for 2 - 4
50% size (gray) for single station
Ellipses - station clustering in first or second cluster
Dashed line - sometimes linked to major region
Solid line - every time linked to major region

Figure 11: Visual representation map of weather station correlations

3.3 Wind

The only wind component that was measured by the IGY teams in 1957 and 1958 was wind speed; direction and gustiness parameters were not recorded. Mean wind speed during 1957 was 6.5 m/s, while mean wind speed for 1958 was 1.8 m/s, though the period of averaging for those two years is not the same. Within these years, the highest recorded wind speed was 20 m/s, occurring on October 3, 1957. This day of high wind is followed by a four more days within the next 15 days with a wind speed higher than 10 m/s. In the 1958 field season, the highest recorded wind speed was 8 m/s. Wind direction at Lake

Peters was not measured until the 1959 season, at which time much more detailed records started to be kept. Wind data were not recorded at Chamberlin Glacier. The wind records from either place would really only be comparable to McCall in the speeds, due to the different orientation and location of the weather stations at Lake Peters and Chamberlin Glacier. This would be useful to compare storm-level synoptics, but daily wind patterns on either glacier are too much dependant upon katabatic winds. Only the strongest synoptic level weather events break through the downslope/upslope daily variations. In 1971, the next time wind data was collected for these stations, the greatest wind speed recorded was 7.5 m/s on June 24, 1971. Neither of the current weather stations on McCall glacier are located in the same place as the first station, which changes how the wind blows across the weather station and hampers direct comparison. The automated station AHAB, sitting on the high ridge, receives much more of the high winds from the upper air than JJMC, sitting in the valley. For the purposes of comparison, JJMC is more likely to be closest to the values of the old wind data. JJMC is still mostly in the throes of the katabatic wind, though it becomes very obvious when that daily cycle is broken by a large wind event.

3.4 Precipitation

The north slope of Alaska has very little snow in general. This has changed very little if at all since IGY. The method of precipitation measurement leaves much to be desired. The amount of snow falling in one snowfall is generally in the mm range, and most of the measured precipitation is rainfall. Lake Peters has much more detailed precipitation data, but as with the wind data, it is relatively incomparable to the McCall Glacier data. The largest amount of precipitation recorded in one day in the 1957/1958 data is 1.4cm on June 24, 1957. The only way to determine whether precipitation might be snowfall is to look at the temperatures and find those below freezing, though this is only a vague estimate, and is not accurate for finding amount of snowfall. The other issue with precipitation is the method of catching the rain or snow. The tipping bucket is inaccurate, especially with the addition of wind. The most accurate measure of snowfall seems to be daily measurements with a depth meter or ruler or the sonic ranger. The current weather stations include a sonic ranger at JJMC and a tipping bucket at AHAB for collecting snow depth data. For graphing purposes, the sonic ranger measurements for McCall Glacier's JJMC station have been multiplied by a factor of 10. In 1996, a sonic ranger was employed to collect snow depth information (Fig. 12).

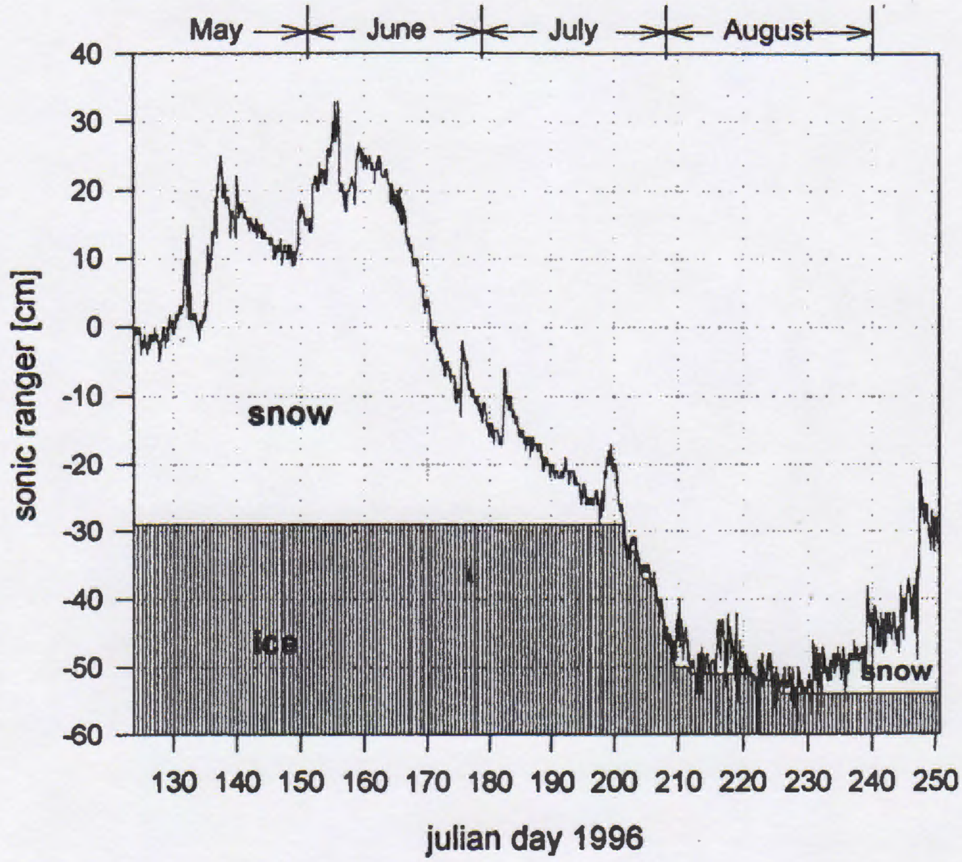


Figure 12: 1996 sonic ranger data from McCall Glacier (Rabus 1997). (Copy of original)

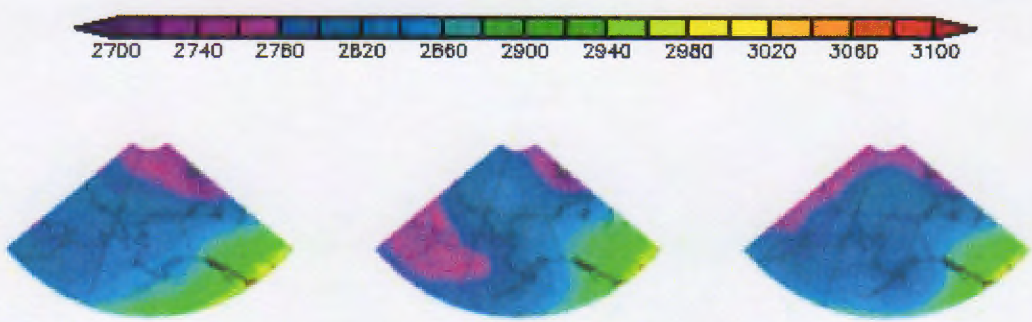
Chapter 4 General Results

4.1 General Synoptic Patterns

In arctic Alaska, the dominant weather pattern is usually based around the Aleutian Low, which is strongest in the winter. There is generally a high pressure system over the Canadian Shield, as well as a high over Siberia. In summer, the Canadian high shifts east over the Archipelago, and all of the pressure gradients decrease.

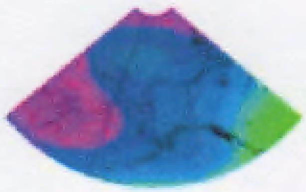
Seasonal average and daily average Geopotential heights are analyzed at 700mb.

4.1.1 October-April

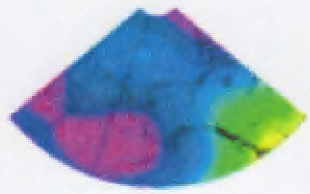


1957 1958 1959

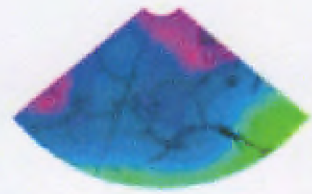
1960 1961 1962



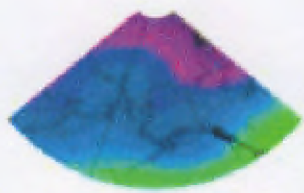
1969



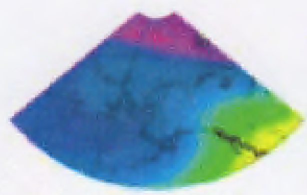
1970



1971



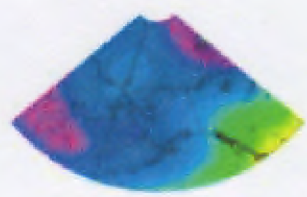
1972



1994

1995

2003

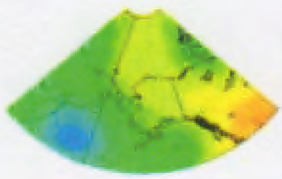


2004

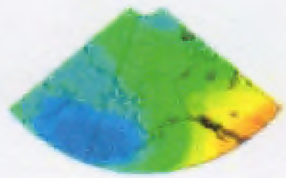
2005

In the period between October and April, the Aleutian Low tends to dominate the Alaskan weather patterns. The years with the greatest variation in the data range seems to be 1957, 1962, and 1972, where high pressure dominates the state, and 1961, 1969, 1970, and 2003, in which the low pressure dominates the state.

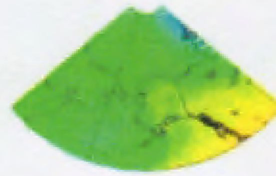
4.1.2 May



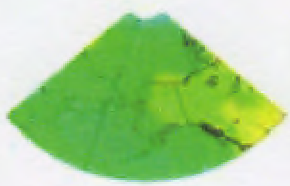
1957



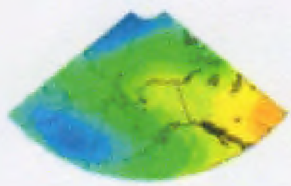
1958



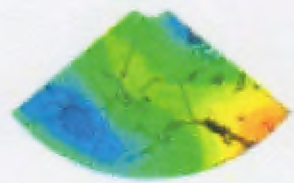
1959



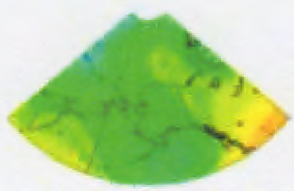
1960



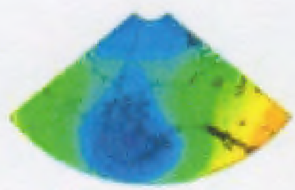
1961



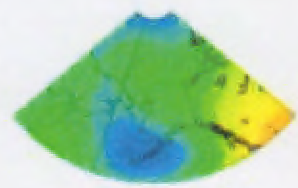
1969



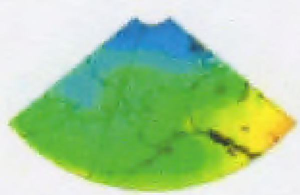
1970



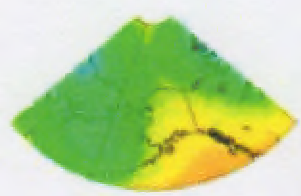
1971



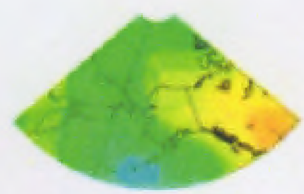
1994



2003



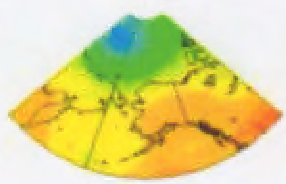
2004



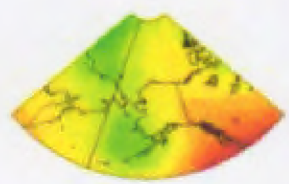
2005

The synoptic patterns in May differ from the patterns in October-April in that the high pressure systems from further south have started moving into Alaska, though the Aleutian Low remains fairly steady in the North Pacific. 1957, 2004, and 2005 are all years with a higher pressure. 1971 has a very low pressure system (for the season) over the Aleutians.

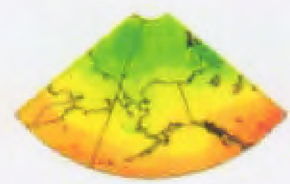
4.1.3 June-August



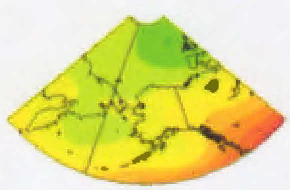
1957



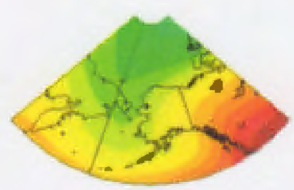
1958



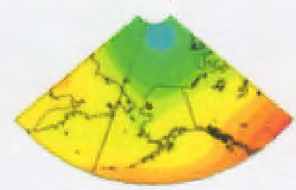
1959



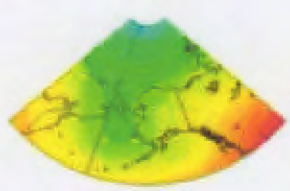
1960



1961

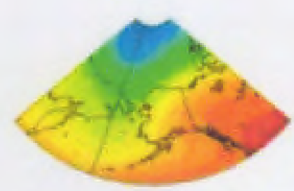


1969

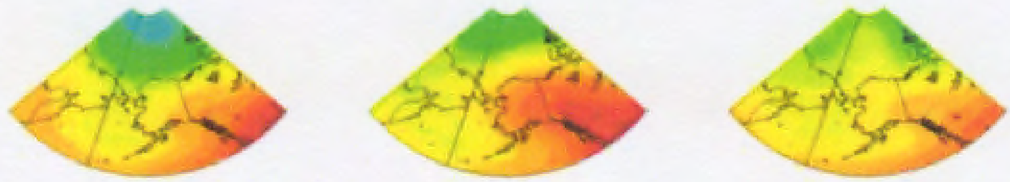


1970

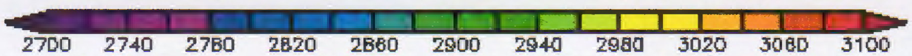
1971



1994

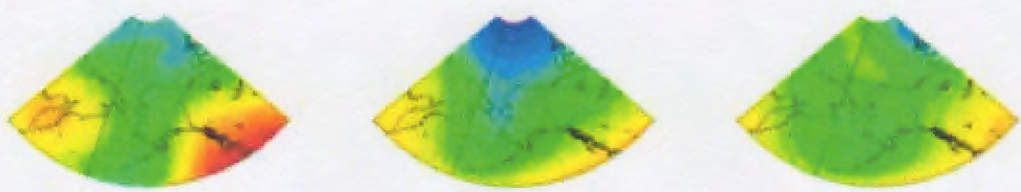


2003 2004 2005

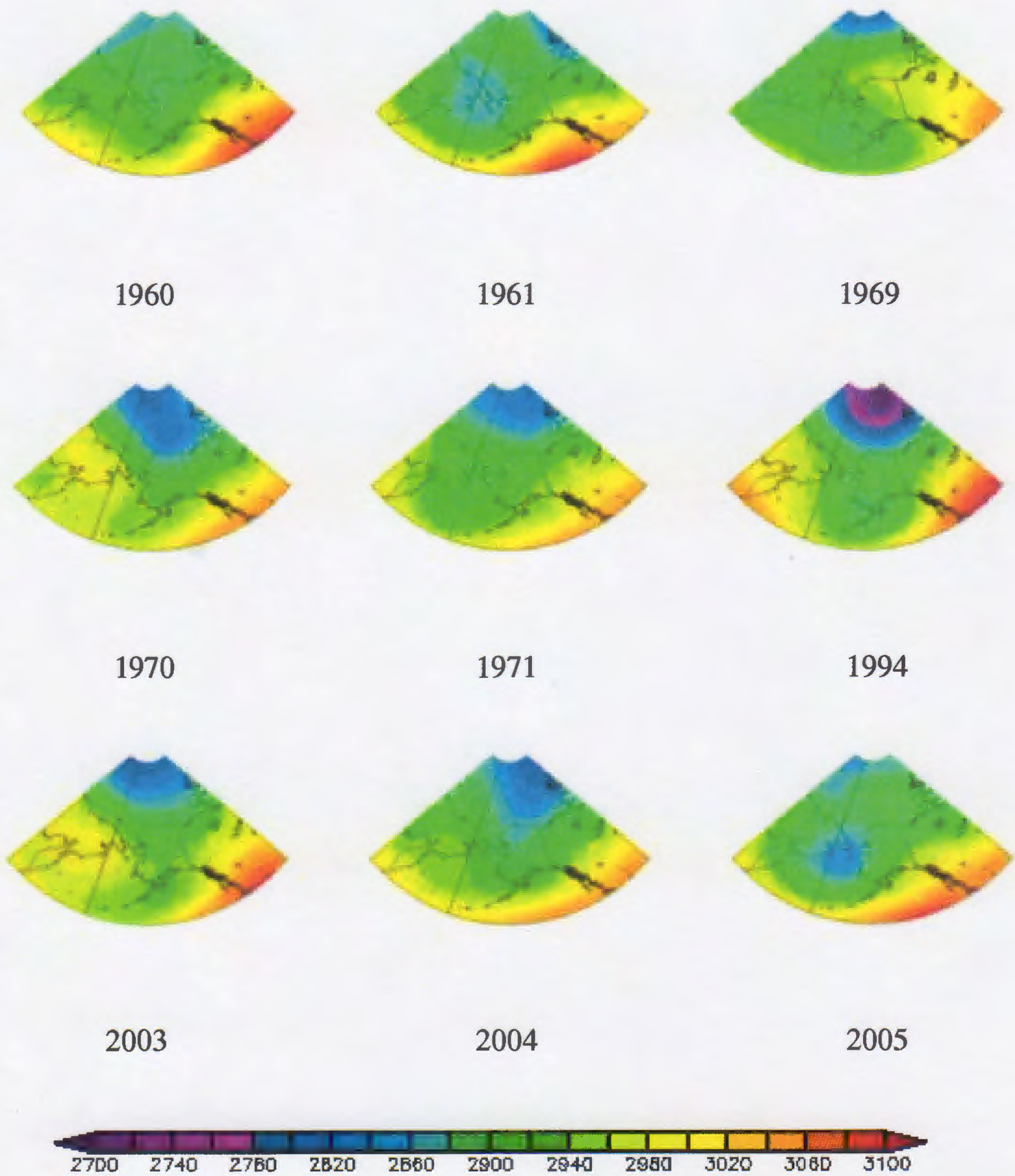


Summer synoptic patterns in Alaska are more often dominated by high pressure systems. 1970 is a lower pressure year than most, while 1994 and 2004 are both dominated by higher pressure.

4.1.4 September



1957 1958 1959

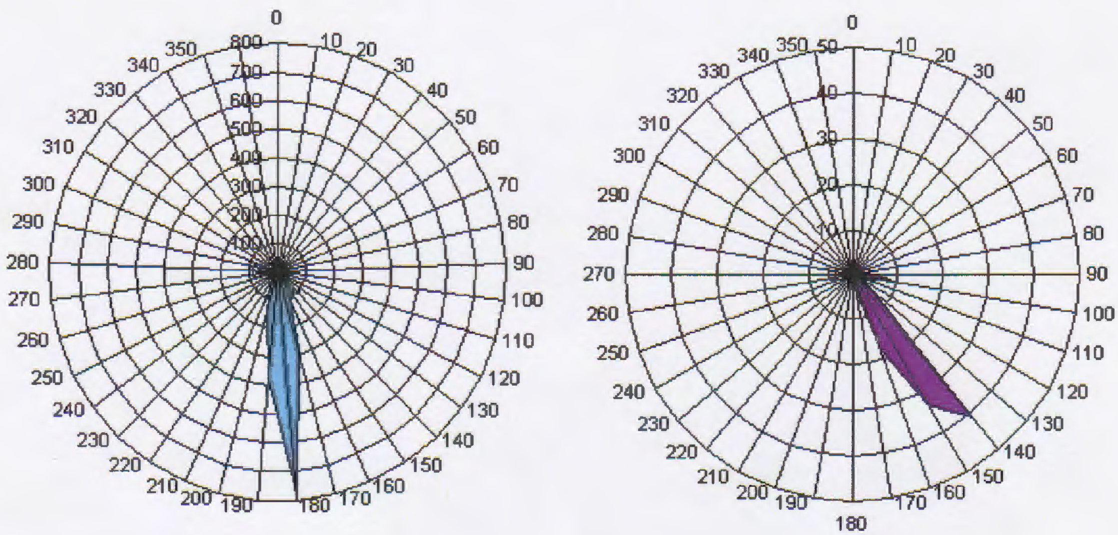


The synoptic patterns for September are the most varied of all the seasons, though the return of a stronger Aleutian Low begins to occur in this month for most years. The Aleutian Low tends to connect with the low north of Alaska in this season.

4.2 Wind patterns

The wind patterns at JJMC and AHAB exhibited a general topographic constraint in their directional component. At JJMC this was most pronounced, with 80% of all wind readings falling in the range of 150-210 degrees, with the average wind direction being 174 degrees. No particular seasonal dependence was observed (Figs. 13 - 17).

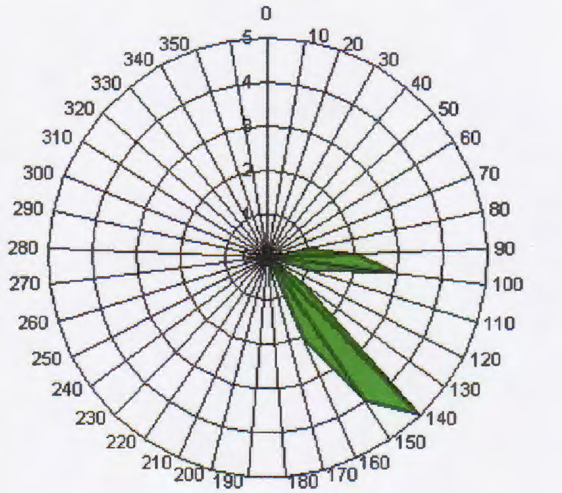
At AHAB, 80% of all wind readings fell in the range of 40-90 degrees, with the average wind direction being 75-80 degrees. 5-10% of wind readings were in the range of 300-330 degrees. From the data available, AHAB summer wind readings shift to either 80 or 330 degrees, though this could be skewed from reader malfunctions.



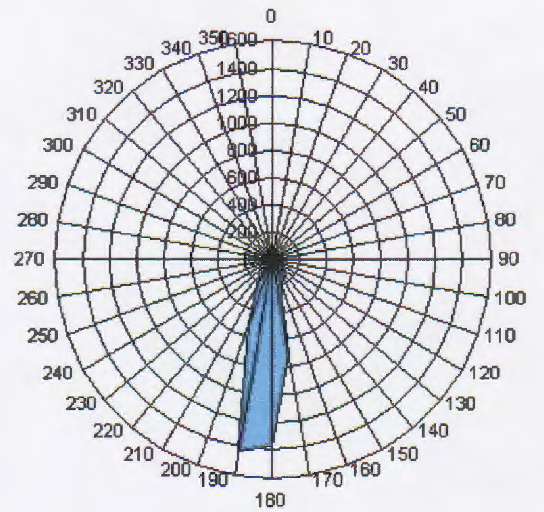
JJMC 2004 Summer winds

Summer winds above 10m/s

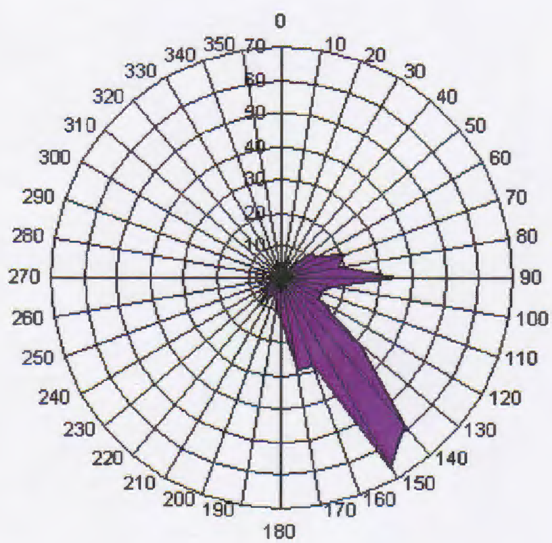
Figure 13: Frequency wind rose for JJMC by season.



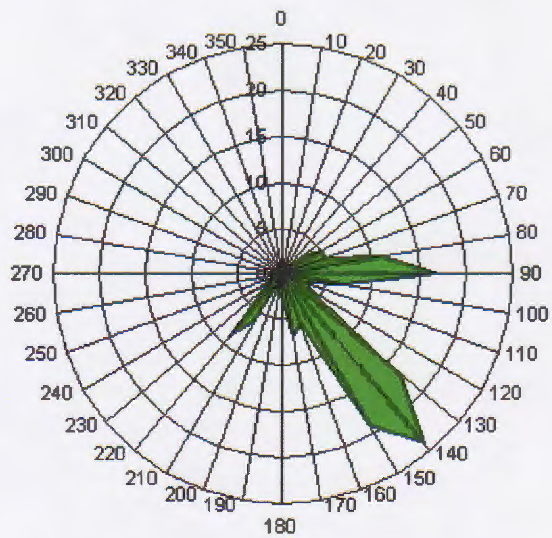
Summer winds above 15m/s



JJMC 2004-05 Winter winds

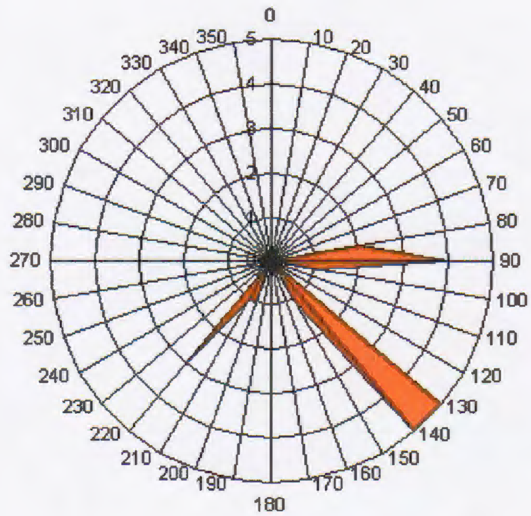


JJMC 2004-05 Winter winds above 10m/s

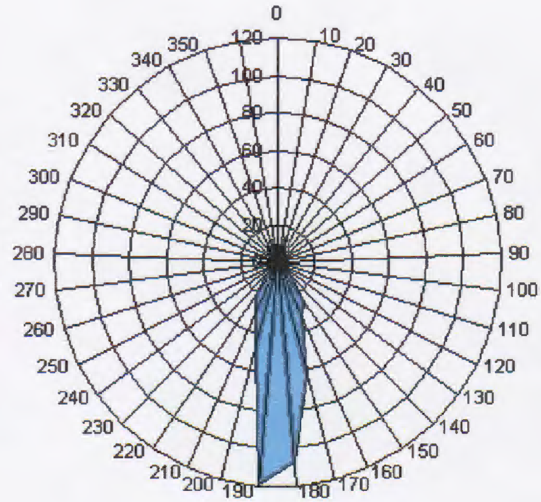


Winter winds above 15m/s

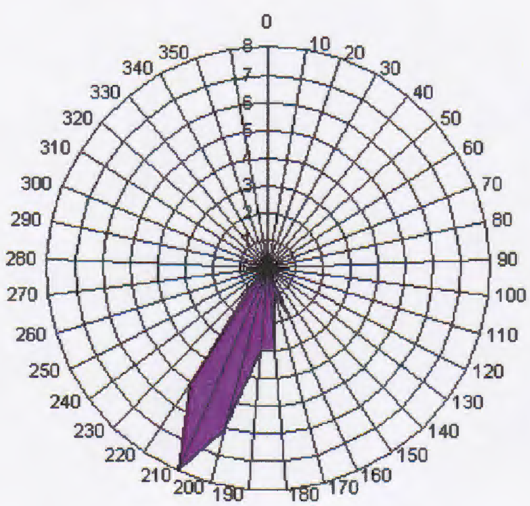
Figure 13 continued.



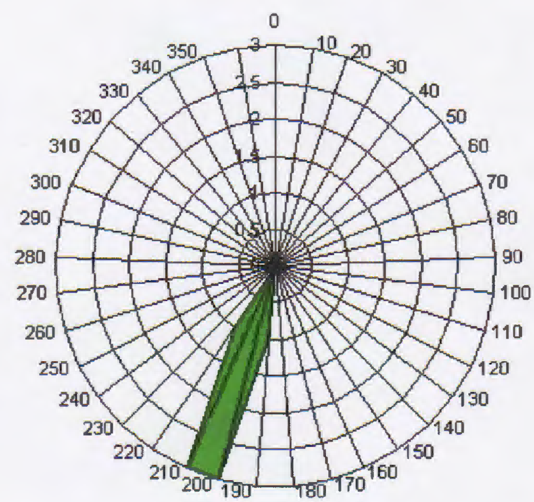
Winter winds above 20m/s



JJMC 2005 Spring winds



Spring winds above 10m/s



Spring winds above 15m/s

Figure 13 continued.

The prevalent direction is in line with the glacier orientation at the JJMC location. This suggests a prevailing down-glacier flow, which is consistent with mass drainage of the cold, denser air nearest the glacier surface. Typical windspeeds are in the 5 to 15m/s range at AHAB and 0 to 5m/s at JJMC. On about 20 occasions during the record, the windspeed at AHAB was observed to exceed 20m/s. During these events the wind direction departed its typically observed range. These occurrences are listed in Table 4.

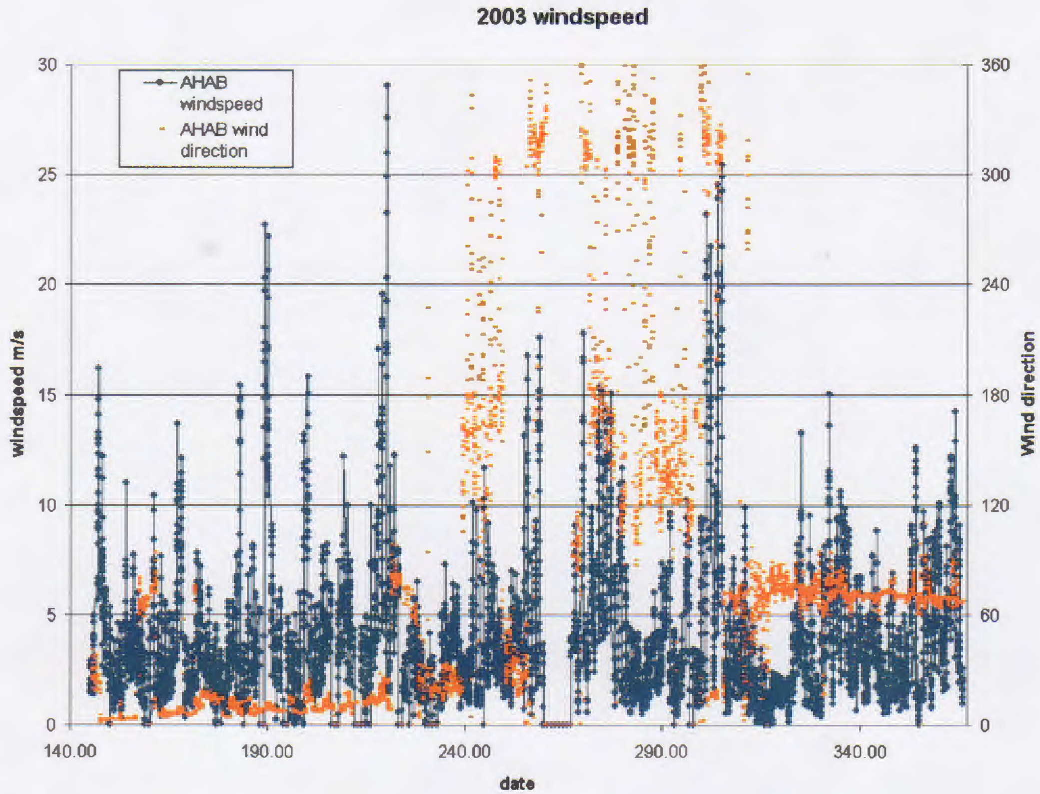


Figure 14: Wind directions and speeds for AHAB 2003.

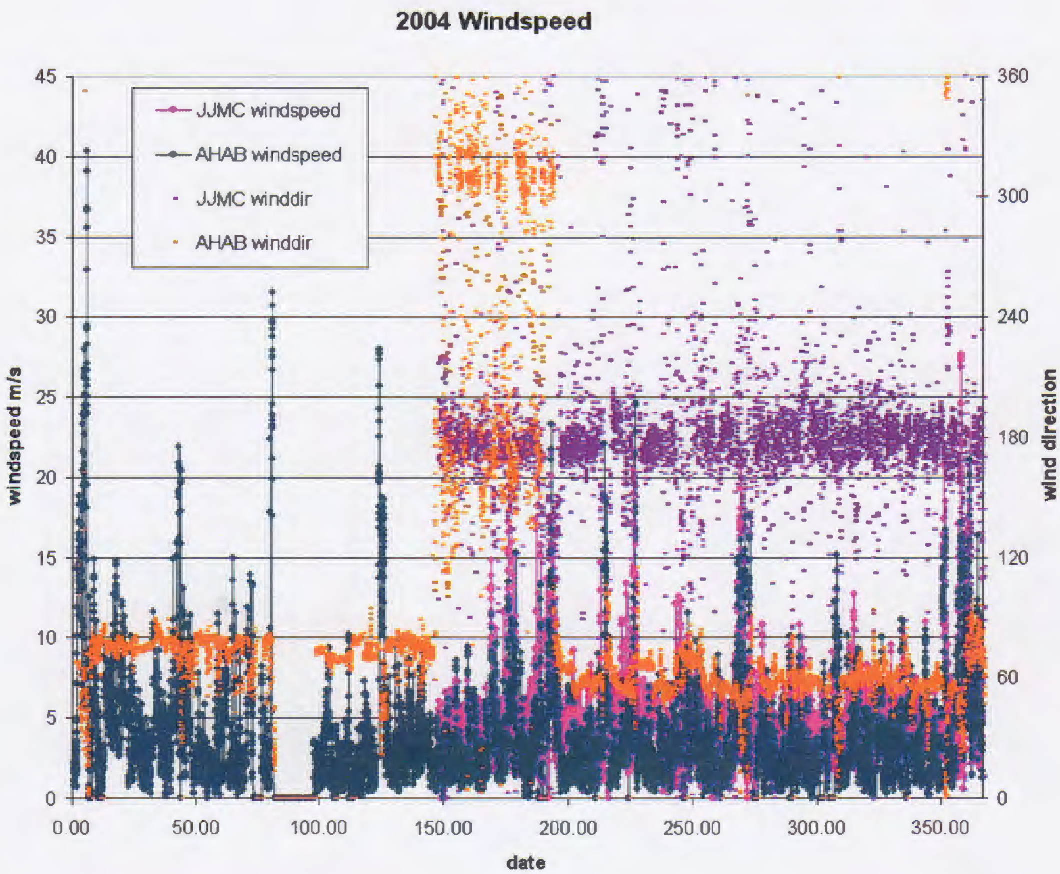


Figure 15: Wind directions and speeds for JJMC and AHAB 2004.

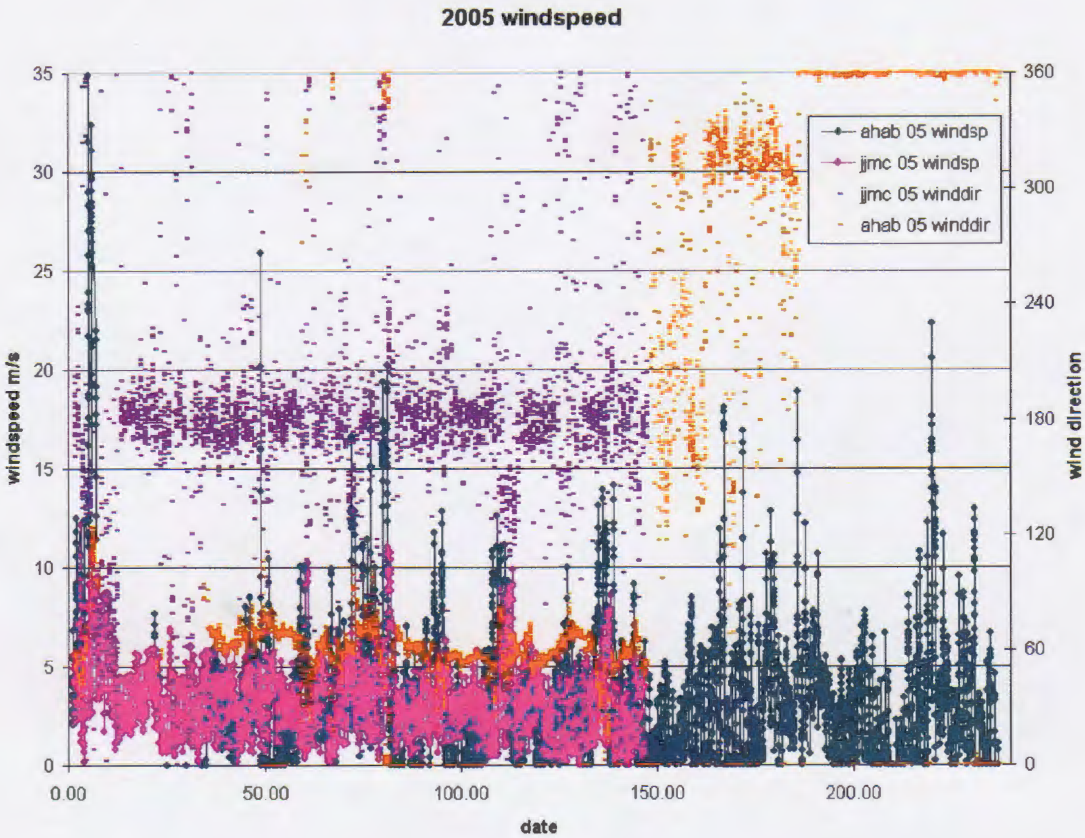


Figure 16: Wind directions and speeds for JJMC and AHAB 2005.

Table 4: Timing, duration, and nature of strong wind events at AHAB and JJMC,

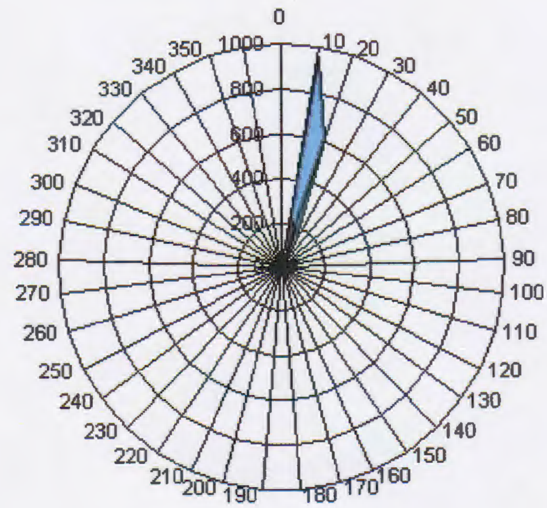
High Wind Events for McCall Glacier, 2003-2005

Date	Location	Duration	Magnitude	Avg Direction
May 27, 2003	AHAB	1 day	16 m/s	30
July 9, 2003	AHAB	2 days	22 m/s	10
July 19, 2003	AHAB	1	16 m/s	25
August 6, 2003	AHAB	3	29 m/s	85
September 16, 2003	AHAB	1	18 m/s	320

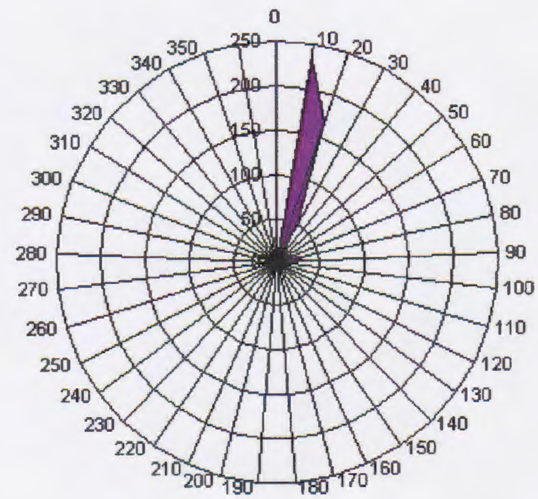
Table 4 continued:

September 27, 2003	AHAB	1	18 m/s	310
October 1, 2003	AHAB	4	15 m/s	180
October 28, 2003	AHAB	6	26 m/s	320
January 2, 2004	AHAB	5	40 m/s	40
February 12, 2004	AHAB	2	22 m/s	40
March 21, 2004	AHAB	2	32 m/s	30
May 4, 2004	AHAB	3	28 m/s	40
July 12, 2004	AHAB & JJMC	3	23 & 20 m/s	100 & 135
August 2, 2004	AHAB	2	22 m/s	95
August 14, 2004	AHAB & JJMC	2	25 & 22 m/s	95 & 135
September 25, 2004	AHAB & JJMC	5	18 & 21 m/s	35 & 145
December 17, 2004	AHAB & JJMC	3	21 & 28 m/s	80 & 135
January 5, 2005	AHAB & JJMC	4	35 & 12 m/s	100 & 80
February 18, 2005	AHAB	1	26 & 12 m/s	100
March 21, 2005	AHAB & JJMC	3	21 m/s	35 & 345
June 16, 2005	AHAB	1	18 m/s	320
June 21, 2005	AHAB	2	17 m/s	320
July 5, 2005	AHAB	1	19 m/s	320
August 8, 2005	AHAB	2	23 m/s	355?

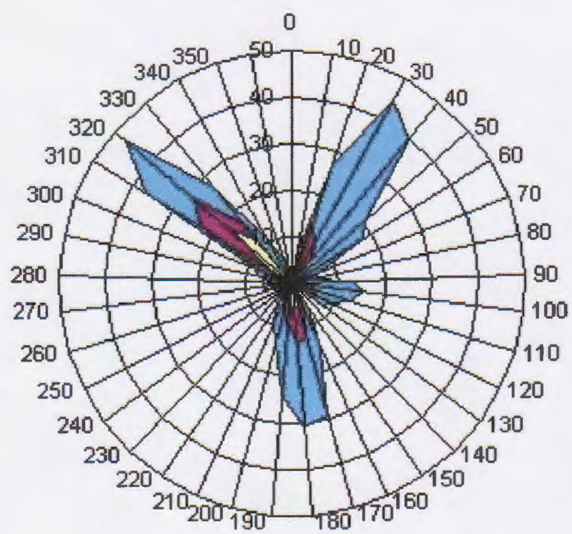
Note: There was a malfunction of direction indicator after July 6 (Julian 187), 2005 at AHAB.



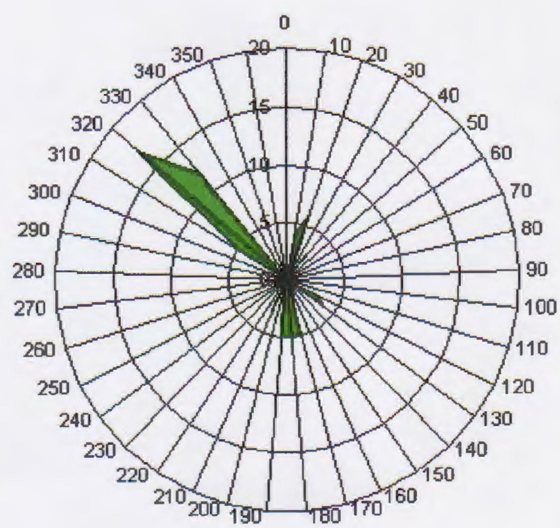
AHAB Summer 2003



Winds above 10m/s

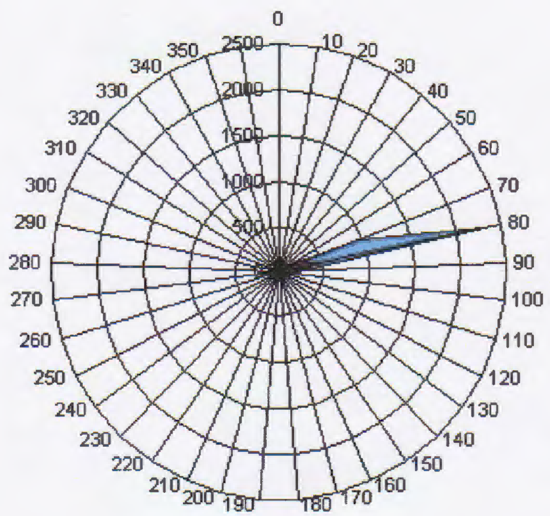


Fall 2003

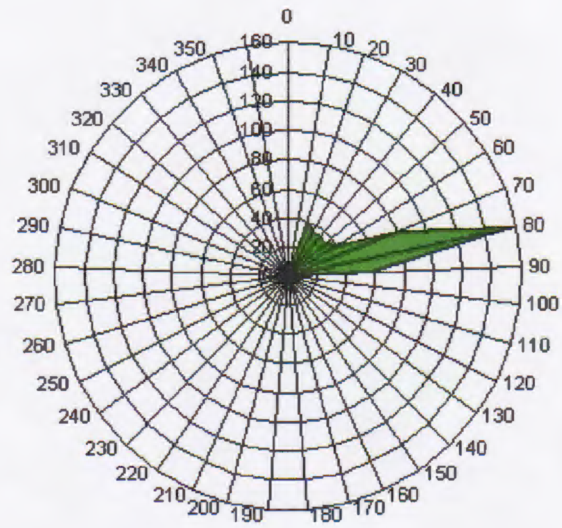


Winds above 15m/s

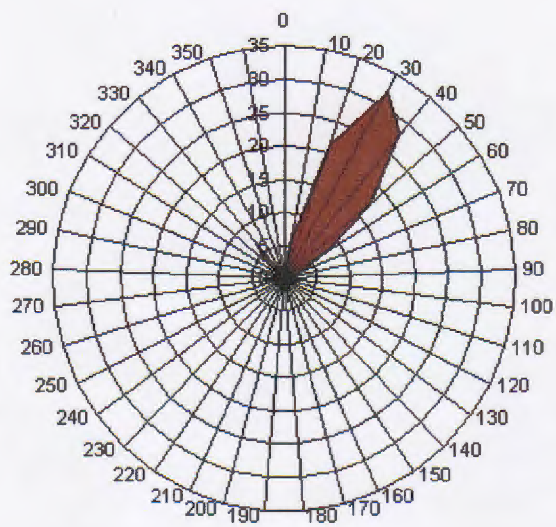
Figure 17: AHAB Wind roses by year and season



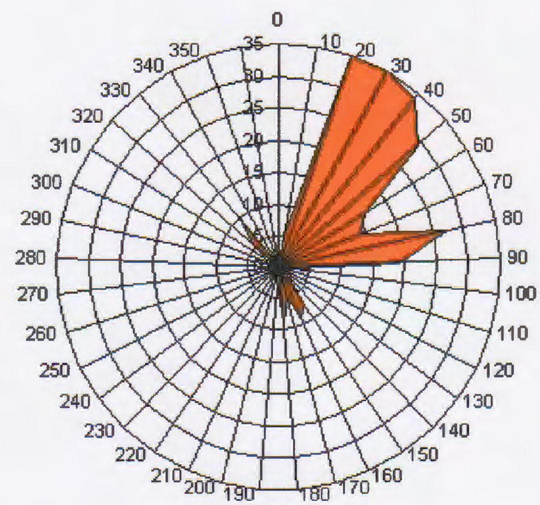
2003-04 Winter



Winds above 15m/s

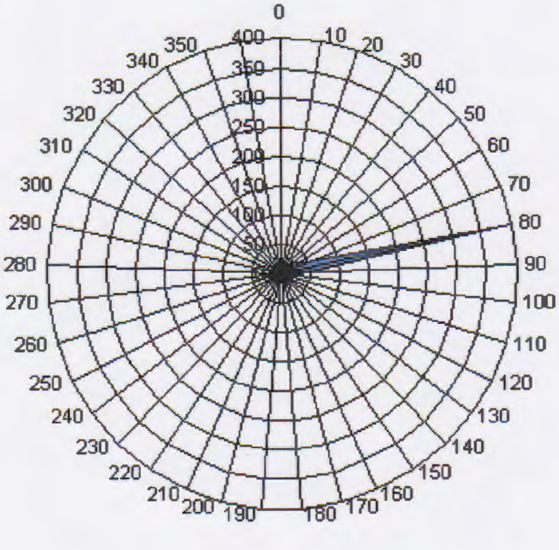


Winds above 20m/s

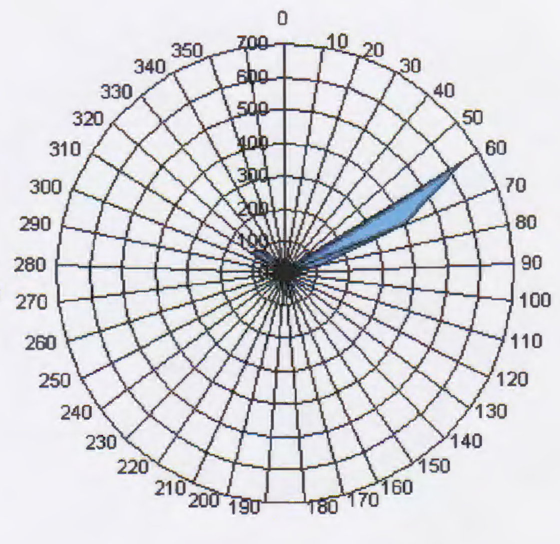


Winds above 25m/s

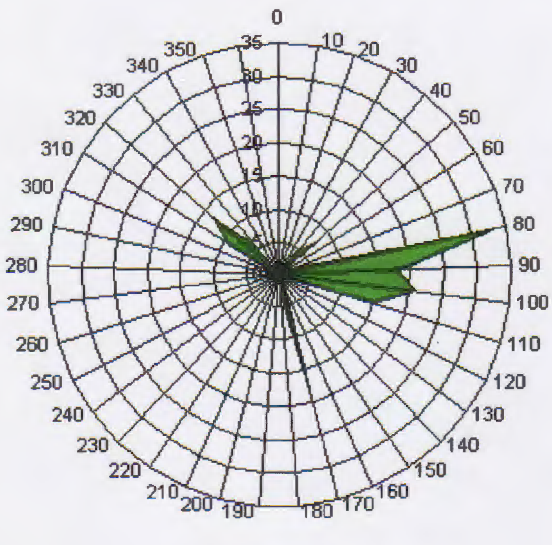
Figure 17 continued.



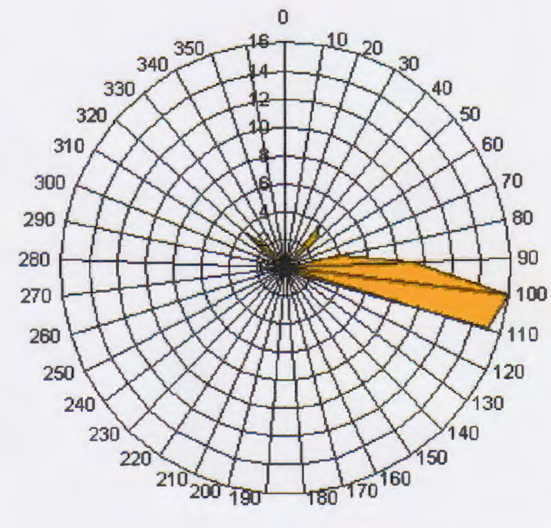
2004 Spring



2004 Summer

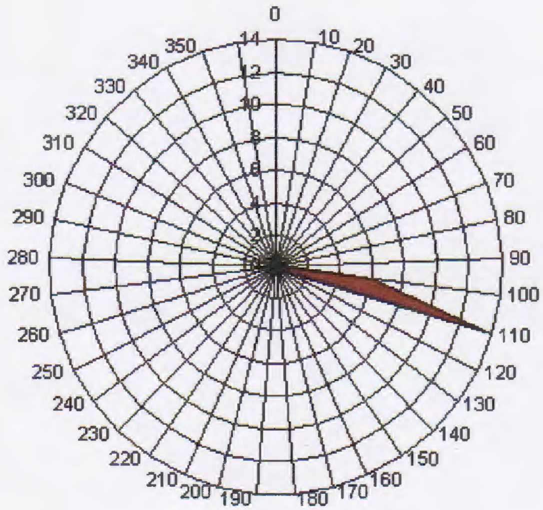


Winds above 15m/s

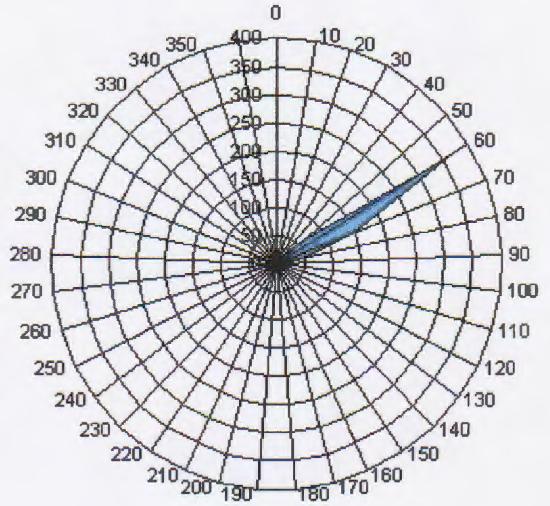


Winds above 20m/s

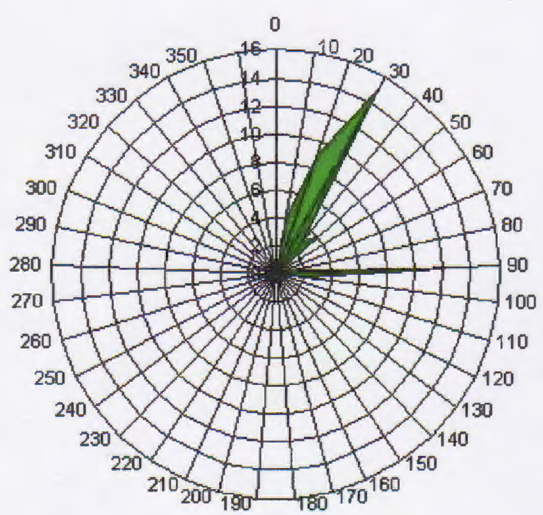
Figure 17 continued.



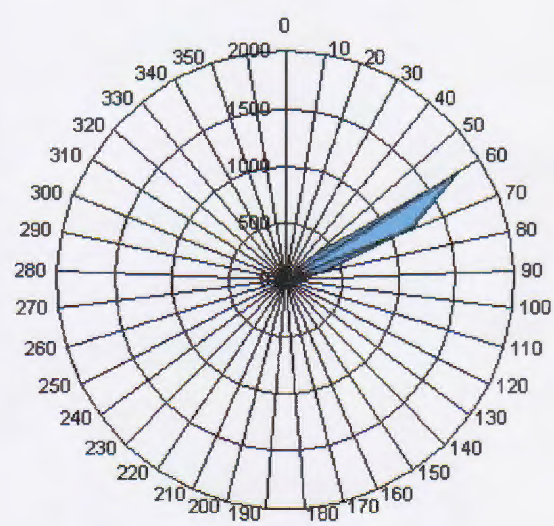
Winds above 25m/s



2004 Fall

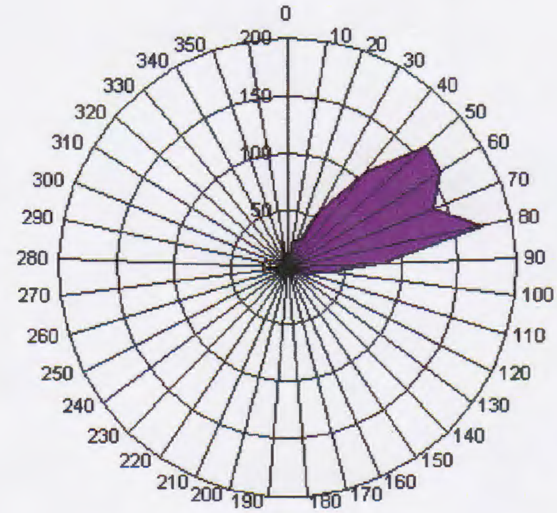


Winds above 15m/s

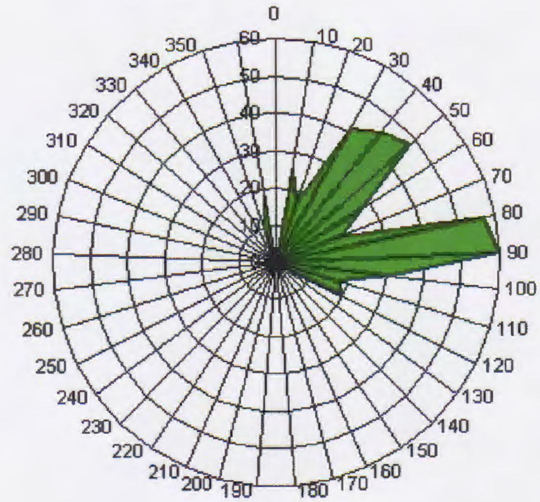


2004-05 Winter

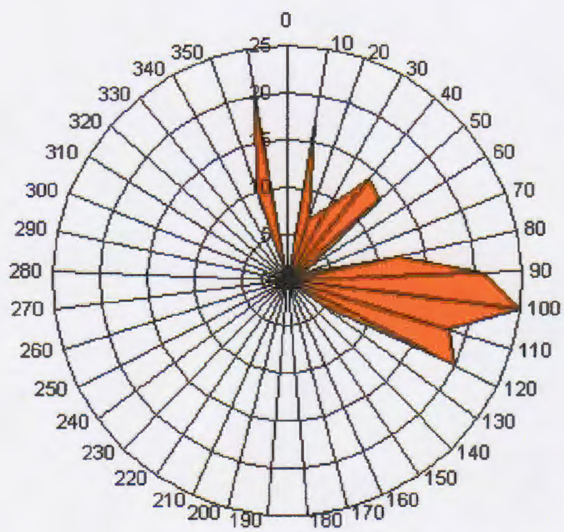
Figure 17 continued.



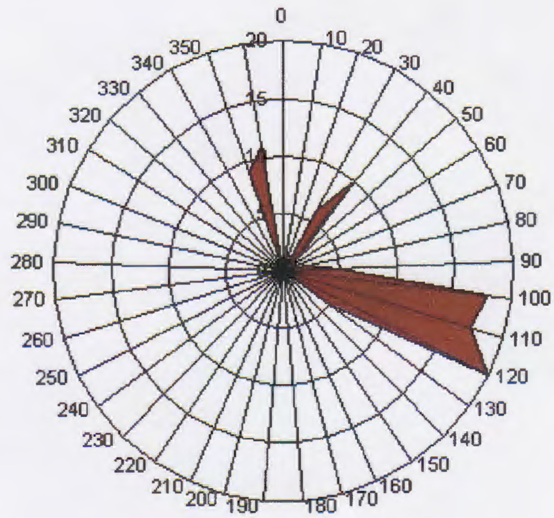
Winds above 10m/s



Winds above 15m/s

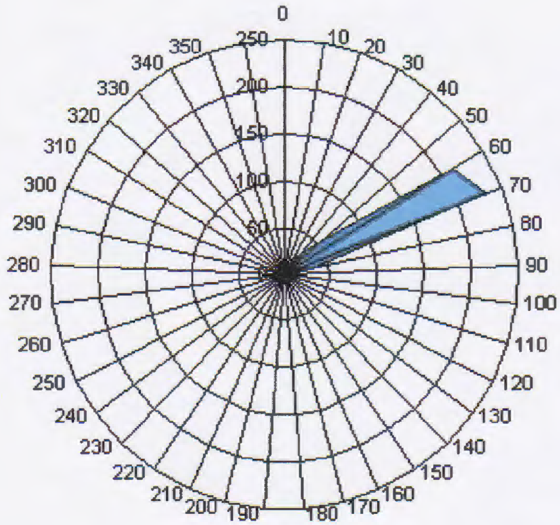


Winds above 20m/s

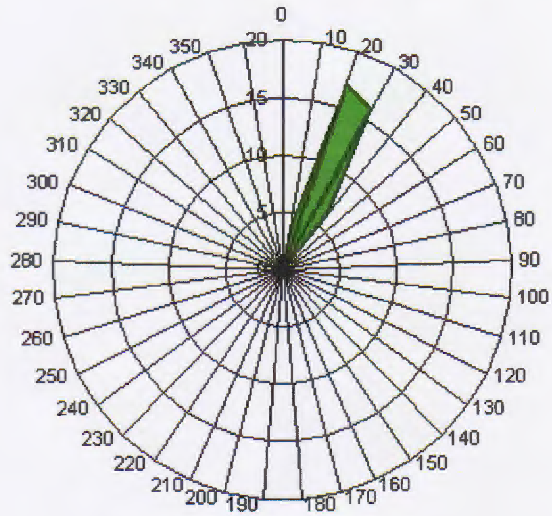


Winds above 25m/s

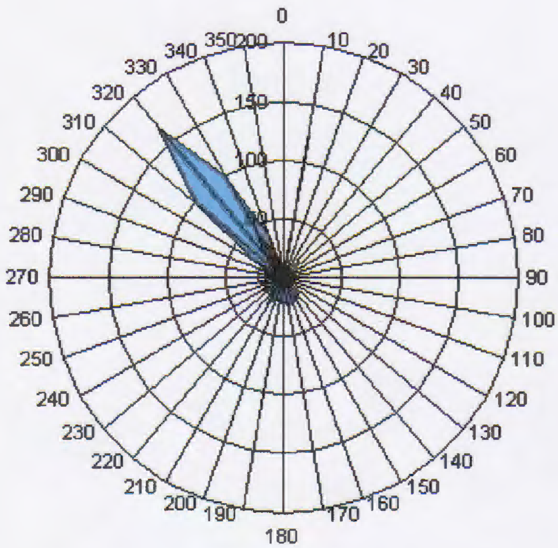
Figure 17 continued.



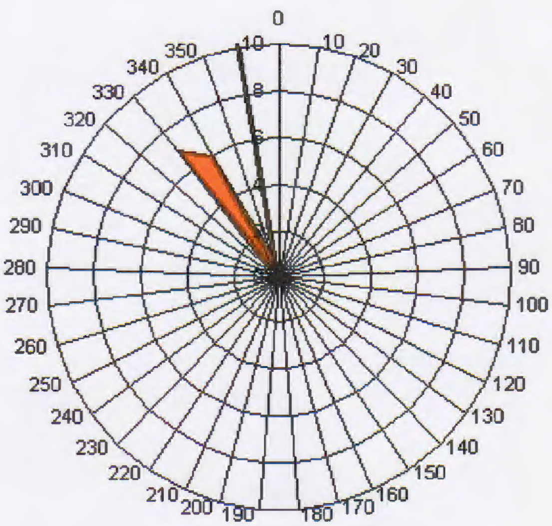
2005 Spring



Winds above 15m/s



2005 Summer



Winds above 20m/s

Figure 17 continued.

4.3 Snowfall

The snowfall record at AHAB and JJMC indicate that snow typically accumulates in episodes of low-rate accumulation events that last several days, rather than infrequent large snowfalls (Fig. 18). Several of these were noted; their timings and durations are listed in the Table 5.

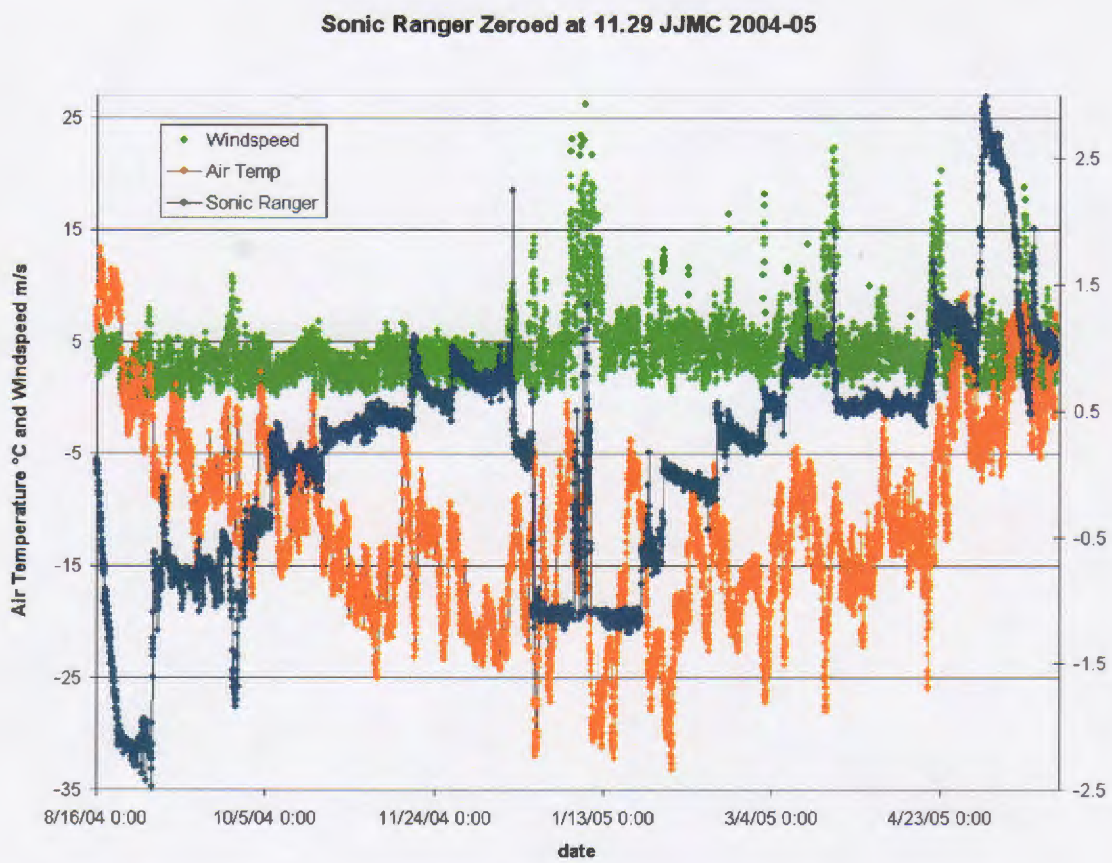


Figure 18: Graph of Sonic Ranger measurements (10x magnification of depths)

Looking at the graphs of the sonic ranger data (Fig. 18), and reading the data notes from Nolan, the tipping of the sonic ranger can be seen to occur from the time of set up until another visit to the site corrected the tilt. The data is considered here to be useable starting August 15th, 2004, at which time the height reads 1.129m.

Table 5: Significant Snowfall Events at JJMC, McCall Glacier 2003-2005

JJMC Snowfall

Date	Julian	mm
9/1/2004	246	13.5
9/4/2004	249	4
9/26/2004	271	8
9/28/2004	273	5
10/6/2004	281	4
10/21/2004	296	4
11/16/2004	322	6
11/28/2004	334	3
12/16/2004	352	16.5
1/4/2005	4	8
1/7/2005	7	8
1/24/2005	24	5
1/30/2005	30	6
2/15/2005	47	7
3/1/2005	61	5
3/8/2005	69	7
3/14/2005	73	5
3/22/2005	81	4
4/21/2005	111	4
5/4/2005	124	10
5/5/2005	125	5
5/9/2005	129	2
5/20/2005	140	6

4.4 Temperature

The temperature record at JJMC and at AHAB indicate a short summer, short shoulder seasons, and a lengthy winter punctuated by occasional warming events during which temperatures rise as much as 30 degrees, up to maxima of -0.5 degrees C (Fig. 19). The strongest warming between 2003 and 2005 occurred at the beginning of October 2003, where the temperature rose 20 degrees C in 4 days. The period between December 24, 2004 and January 30, 2005 experienced four 30 degree temperature swings. The middle of winter 2003-2004 did not experience quite as large a swing, with only one 20 degree swing in the same time period.

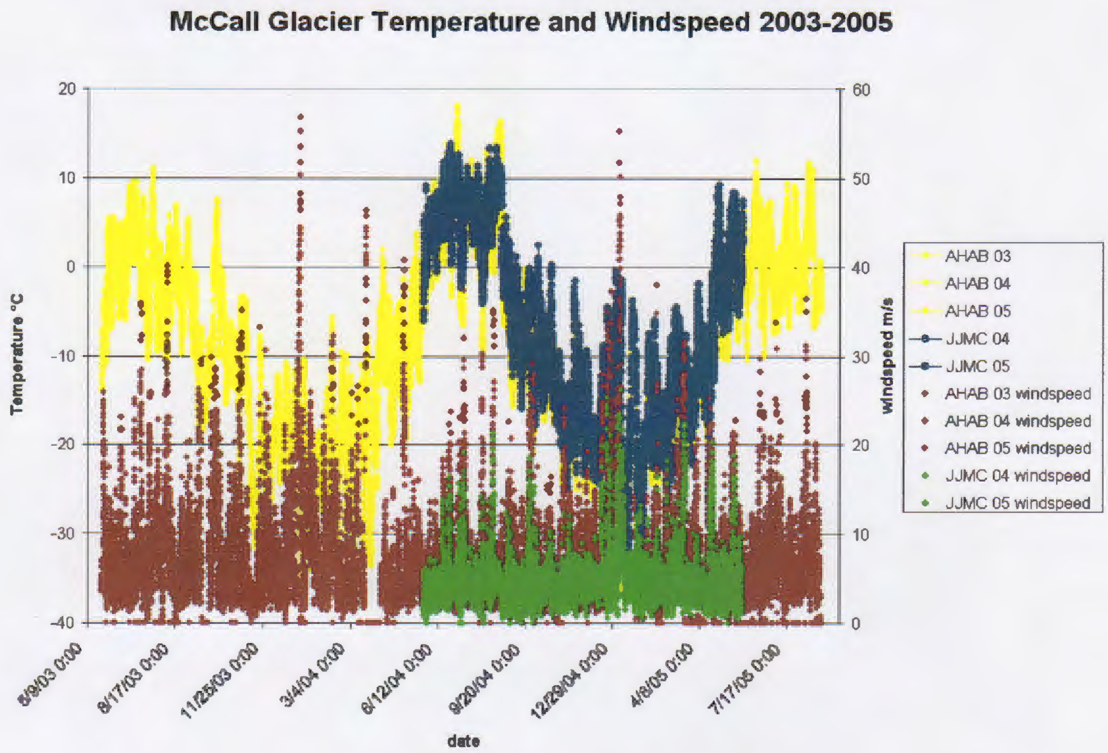


Figure 19: Plot of temperature traces and wind speed for JJMC and AHAB 2003-2005

Table 6: Average Monthly Temperature (in degrees C) at McCall Glacier and Lake Peters for all available data. M indicates McCall Glacier, C indicates Chamberlin Glacier, and P indicates Lake Peters.

	1957M	1958M	1958C	1958P	1959P	1960P	1961P	1971M	2003M	2004M	2005M
Jan							-29.8			-23.4	-19.5
Feb							-33.9			-20	-18.1
March							-31.4			-22	-15.9
April		-15.0			-12.5	-8.3	-27.3			-10.8	-9.5
May		-7.0			-5.6	-3.4	-2.3		-5.5	-2.6	-1.6
June	-3.0	3.4			5.2	4.4	6.2	2	0.3	5.4	1.2
July	1.5	3.2	5.6	10.3	5.4	6.9	8.7	4.2	-0.2	4.6	-0.3
Aug	1.6	2.6	4.1	9.3	5.7	4.9	6.2		-2	3.7	0.3
Sept	-8.1					-2.2			-9.8	-9.0	
Oct	-11.6					-15.6			-8.5	-11.8	
Nov						-29.4			-20.2	-16.7	
Dec						-18.5			-19.2	-19.6	

As Table 6 shows, the monthly average temperatures for 1957 and 1958 are quite different, though between 1957 and 2005, the monthly average fluctuations don't vary much over time. The temperatures at Lake Peters are somewhat skewed, as they occur on the shores of the lake much lower in elevation than McCall Glacier. The average monthly temperatures at Lake Peters are warmer in spring, summer, and fall, and cooler in winter than McCall. The months for which there is data at Chamberlin Glacier, the temperature is cooler by an average of 5 degrees C than the temperature at Lake Peters and 2 degrees C warmer than McCall. September at McCall was colder in 2004 and 2005 than in 1957. The spring of 1958 at McCall was colder by about 5 degrees C than the springs of 2004 and 2005. The warmest summer on record at McCall was 2004, with the coldest being in 1957, though 1958 was warmer than both 2003 and 2005 at McCall. The summer of 1958 at Lake Peters was much warmer than others on record, with the June-August average being 9.8 degrees C, as compared to 5.4° C for both 1959 and 1960, and 7.0° C for 1961 (Fig. 20). In most cases, July was the warmest months, with a few exceptions where August was slightly warmer.

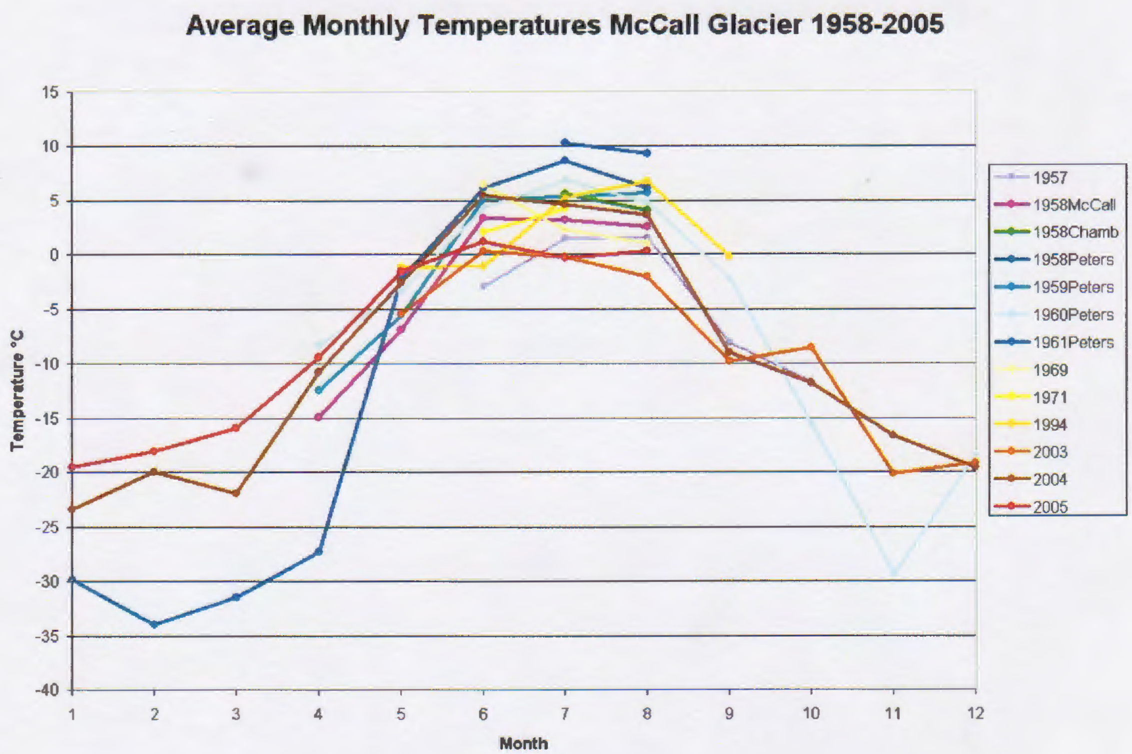


Figure 20: Average monthly temperatures of McCall Glacier and Lake Peters 1958-2005

4.5 1971 Data

The winds during this period of data (June 17 through July 22) were between 0 and 7.5m/s, with the average windspeed being 3.2m/s. Monthly average temperatures are

5.2 °C maximum and -1.2 °C minimum for June 1971, and the average maximum is 7.4 °C and .9 °C minimum for July 1971. The maximum daily temperature for this period is 12.5 °C, with the minimum being -10 °C. From the vapor pressure data, it does not look like much precipitation occurred during this time period, though the most likely day of precipitation would have been July 21st (Fig. 21). Looking at the CDC daily climate composites for this period, the glacier is under a high pressure system for most of this time period, with very low winds and very little precipitation. According to the composites, a low approached from the north around June 27, which only lasted a few days and did not seem to bring any moisture, after which high pressure prevailed for the month of July.

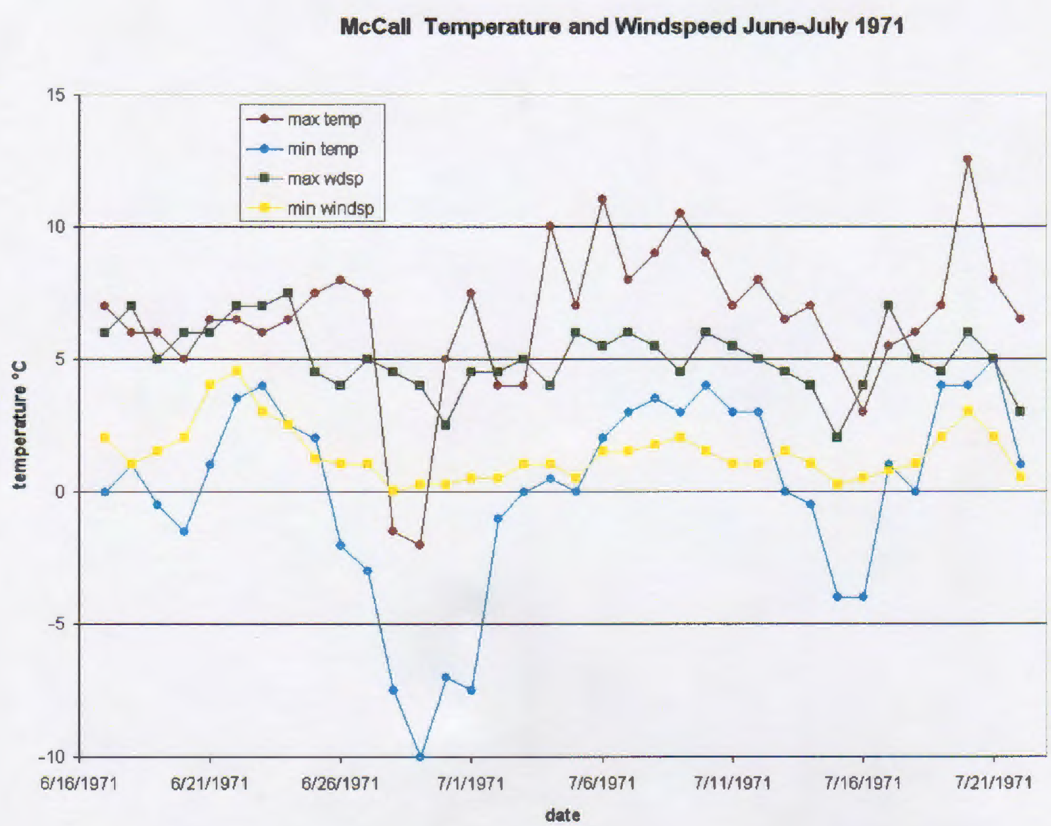


Fig 21: McCall temperature and windspeed chart for June and July 1971.

Chapter 5 Analyzed Storm Events, 2003-2005

A relevant weather event in this context is one which can act on the mass balance of the glacier. This includes snowfall events (accumulation), high wind events (scour), high temperature events (melt). The prevailing synoptic flow patterns are examined below for each weather event identified in the following tables. The synoptic charts are 12 hours ahead of local glacier time.

5.1 July 4-12, 2004

During the period 3-13 July, 2004, a series of several weather events occurred that brought large temperature variations and strong winds that scoured and deposited snow (Fig. 22). Flow during this entire period was generally from the west but subtle changes in direction accounted for the large temperature variations and snowfall as net advection was sometimes from the northwest and sometimes from the southwest. This brought, in turn, very warm air from the interior or relatively cool air from the Chukchi Sea.

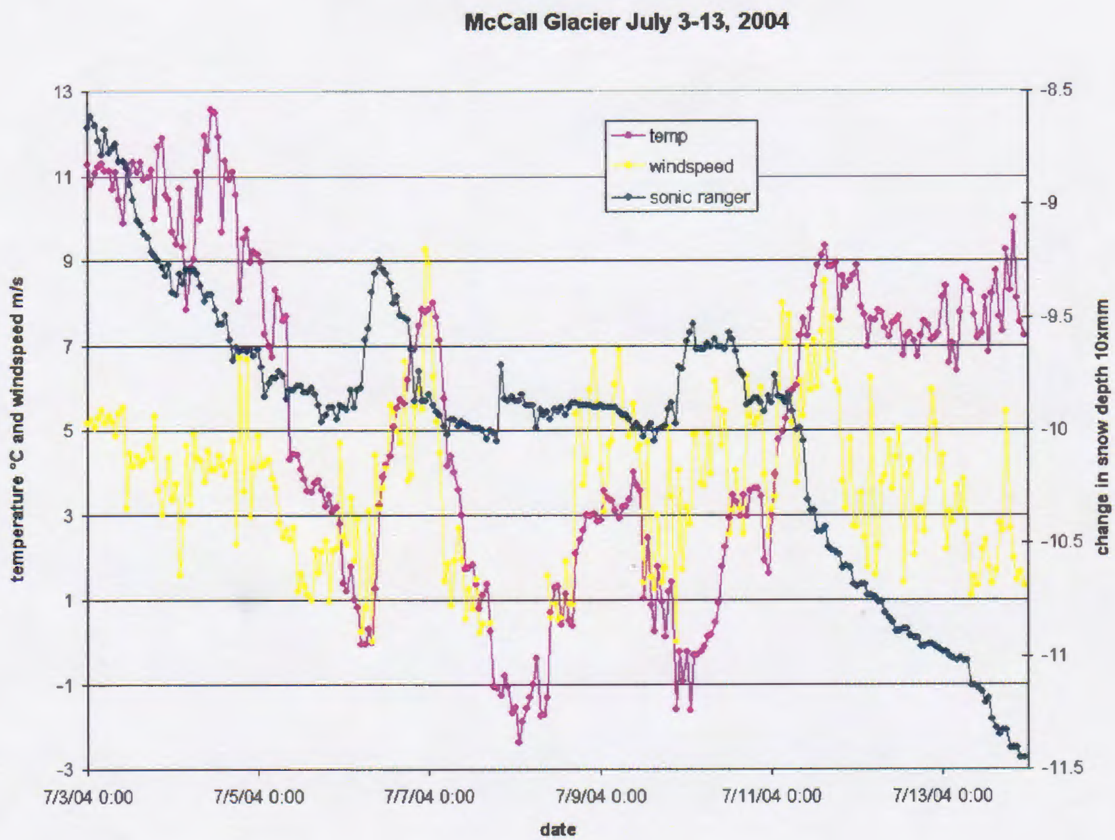


Figure 22: Air temperature, wind speed and snow depth from JJMC station, McCall Glacier, July 3 – 13, 2004.

5.1.1 Wind speed and direction

Average wind direction for 2004 at JJMC is 172°. During the period July 6-10 the average wind direction at JJMC was 140°. AHAB's wind readings were skewed due to a probable riming event between the 7th and the 8th. The data values for wind during the event were zero for most temperatures under 0° C. The relative humidity was very high during this event. AHAB and JJMC both had wind speed maximums on July 6 and

11, AHAB reaching speeds of 23.1 and 37.4 m/s, respectively. JJMC high wind speeds were 9.3 m/s and 8.5 m/s.

5.1.2 Temperature

This event started with a high temperature of 12.6° C on July 4, which dropped below zero by 6am on the 6th, just as the first snowfall was occurring. Over the next 18 hours the temperature rose to 8° C by 1am the next morning and then dropped again to -2.4° C over the next 24 hours. The second, smaller snowfall corresponds with the lowest temperatures in this period. The next temperature maxima occurred at 3pm July 9th, when the temperature rose to 4° C. The temperature again dropped 5.6° C by the 10th at 1am to -1.6° C. The third snowfall corresponds with this low temperature. After this third low, the temperature climbs back to 9.3° C by 3pm on July 11th, marking an end of this summer snowfall event.

5.1.3 Precipitation

Precipitation, expressed as snow depth, varied during this period and may be broken down in to seven timeframes:

1) Event begins with steady decrease in depth (July 3-5)

2) Rapid increase/snowfall (July 6)

3) Rapid decrease followed by slight decrease (July 7)

4) Rapid small increase (end of July 7)

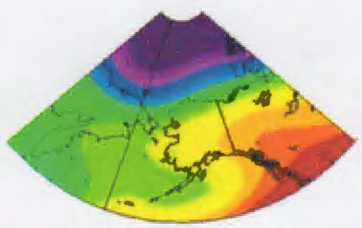
5) Steady decrease (July 8-9)

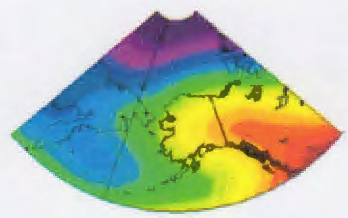
6) Rapid increase (July 10)

7) Rapid decrease followed by steady decrease (July 11-13)

As the temperature drops, the sonic ranger measured snow depth increases. Each time the temperature drops below 0° C during this period, a snowfall event occurs. The decrease in snowfall in period 3) corresponds with an increase in wind speed.

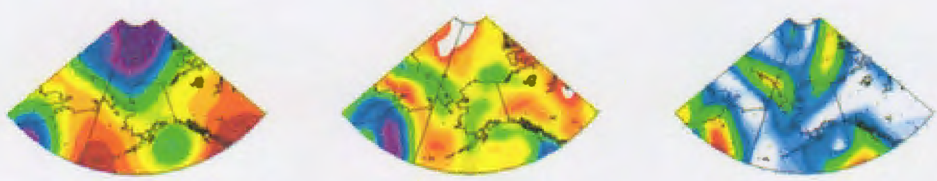
5.1.4 Storm synoptic progression



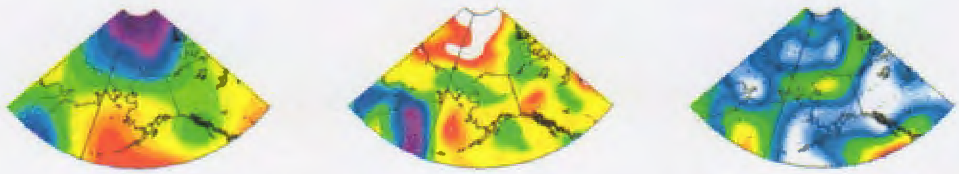


July 2004 June-August 2004

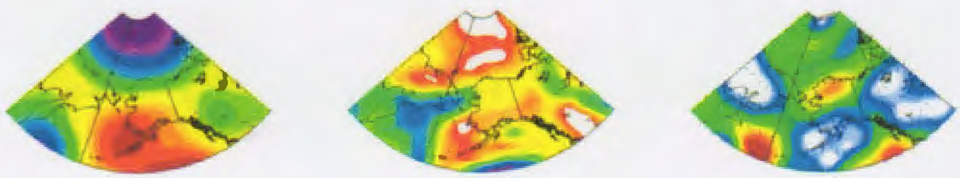
For all July days listed, the synoptic charts are geopotential height, precipitable water, and vector wind, all plotted at 700mb.



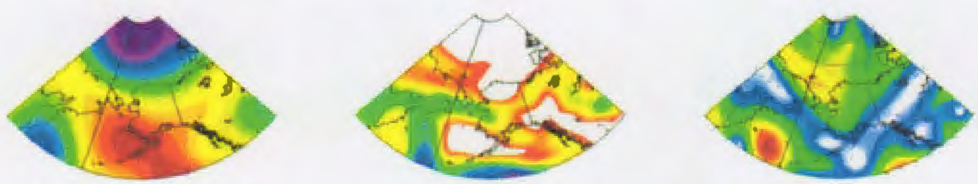
July 5- A low in Chukchi Sea area (a) moves moisture into the western and northern part of the state (b). This advected air is also cool, resulting in the observed temperature drop (Fig 22).



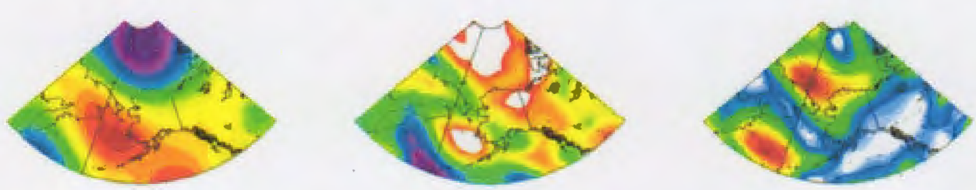
July 6- Westerly winds have intensified across the northern part of the state (c). The rate of temperature decrease increases, resulting in the beginning of snowfall (Fig. 22) as relative humidity rises to condensation.



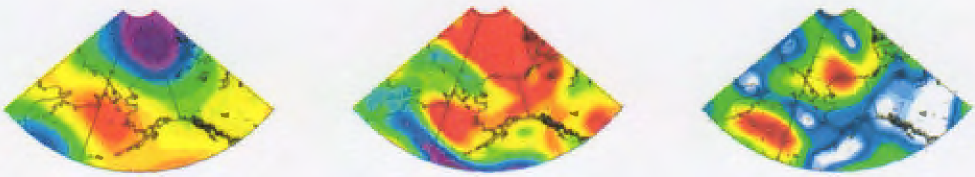
July 7- A slight wind shift favoring a greater southerly component to the flow results in a rapid increase in temperatures and an associated cessation of snowfall.



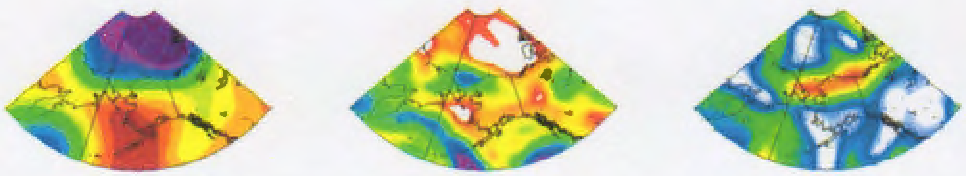
July 8- slight shift of high pressure system to further north, wind speed drops



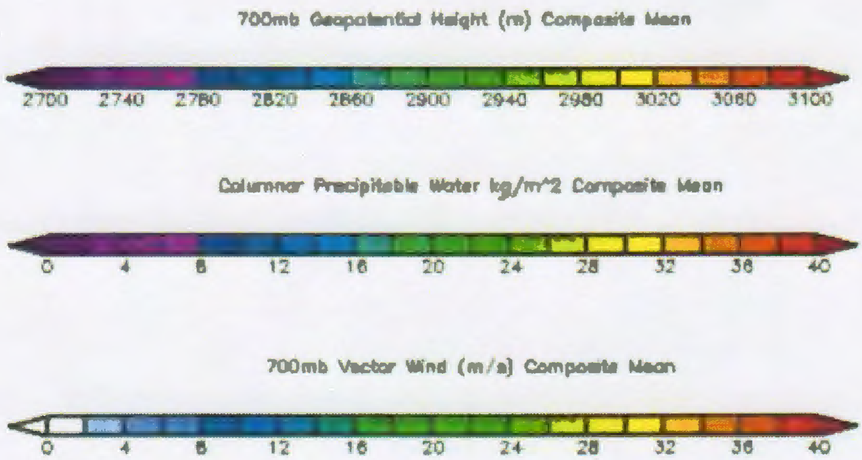
July 9- high pressure system moves further north still, winds not as favorable for moisture-laden system over the Brooks Range, as they are almost directly from the west.



July 10- wind shift, now from further north, bringing moisture from the Beaufort, corresponding with the slight snowfall.



July 11- wind shift, from further south, bringing warmer temperatures and snowmelt.



5.2 September 20-30, 2004

During the period 20 – 30 September, 2004, several weather events occurred that brought large temperature variations and strong winds that initially greatly reduced snow cover and then replaced lost snow cover with fresh snowfall (Fig. 23).

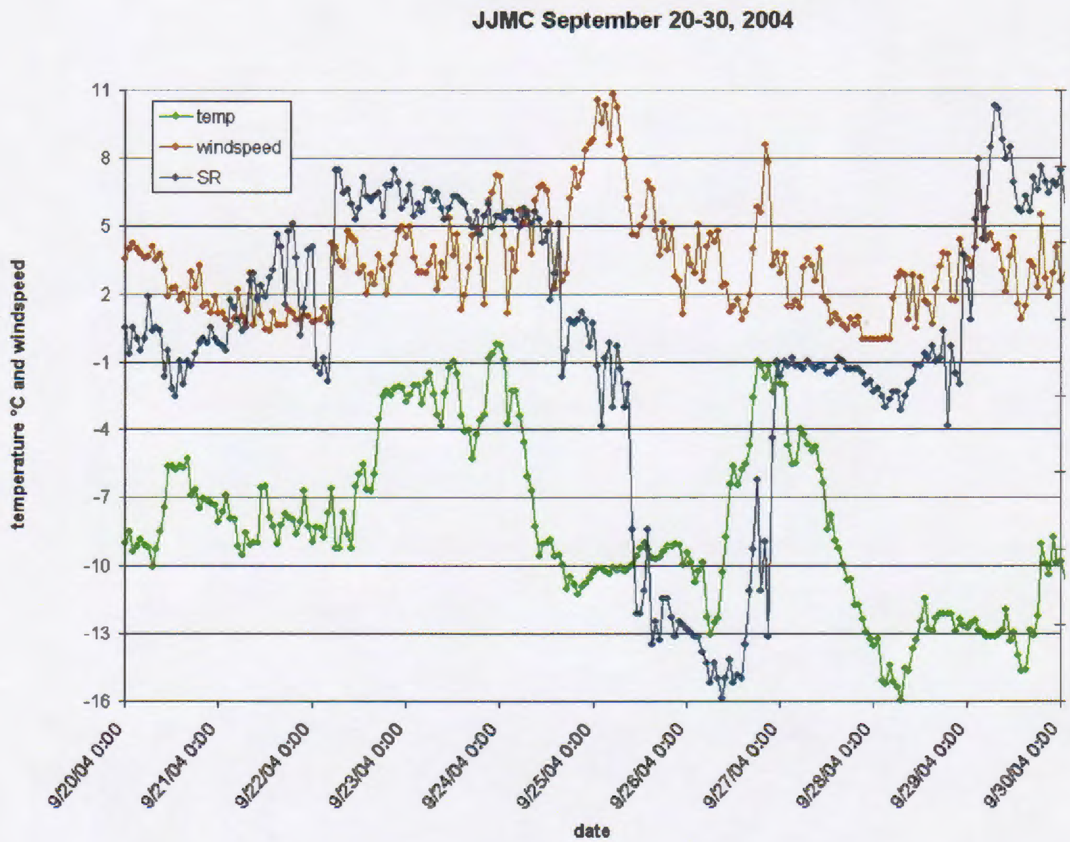


Figure 23: Air temperature, wind speed and inverse snow depth from JJMC station, McCall Glacier, September 20 – 30, 2004.

5.2.1 Wind Direction

Wind directions at both glacier meteorology sites exhibited change from their topographically dominated regimes, backing by as much as 40°. The average wind direction at AHAB for the period between 2003 and 2005 is 74°, while during the period September 20-30, 2004, the average wind direction at AHAB was 48°, backing even further to 36° on the 25th of September. At JJMC, the average wind direction during 2004 was 174°, while during September, the average wind direction was 172°, though on the 25th of September the average wind direction was 148°.

5.2.2 Wind Speed

Wind speeds during this entire period ranged from a low of 0 to a high of 11m/s at JJMC. During much of the time wind speeds were elevated above the average speeds. Peak winds up to 10.79 m/s occurred over an extended period during the last part of Sept. 24 into Sept. 25, with a short secondary peak up to 8.59 m/s occurring late Sept. 26.

5.2.3 Precipitation

Precipitation, expressed as snow depth, varied during this period and may be broken down in to six timeframes:

1) Initial increase as the event begins (Sept 20 – 22).
2) Rapid increase (Sept 22)
3) Stable, slightly decreasing period (Sept 22 – 24).
4) Rapid decrease (Sept 24 – 27)
5) Rapid increase (Sept 26 – 27)
6) Steady (Sept 27-29)
7) Secondary rapid increase (Sept 29 - 30)

The decreases in snow depth are typically, but not exclusively, correlated with higher wind speeds. Precipitation period 3) above is correlated with a gradual increase in wind speeds over these two days and an initial loss of 4cm of snow. The large decreases observed in precipitation period 4) are similarly correlated with the period of strongest winds – a total decrease of 12.4cm of snow, 11cm of which was within the first 24 hours. The rapid increase observed during precipitation period 5) was also interrupted and reversed for a few hours by the secondary wind speed maxima.

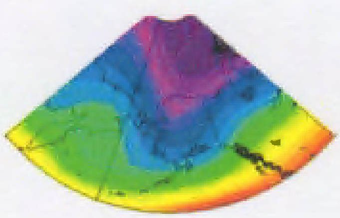
The initial increase in snow depth of 5.5cm on September 22, marking the beginning of precipitation period 2), corresponds to a wind speed and temperature increase. The large temperature drop of 11° C, which commenced on the Sept. 24, also corresponded to the windiest part of the month, after which the temperature increased again.

The wind speed during this 10-day period reached a maximum of 11 m/s on September 25th at JJMC. At AHAB, the maximum wind of 29.2 m/s for this period occurred on the 26th, while the JJMC wind speed maximum corresponded with a maximum speed of 26 m/s at AHAB.

The minimum snow depth during this 10-day period corresponds with the minimum temperature during the period. With the increase in temperature from -13° to -1° C, the snow pack increased 8.8cm within 12 hours. This snowfall was interrupted in the middle by a 9 m/s wind that lasted 7 hours, scouring 4.1cm of snow away. Due to the nature of snow measurements, it is practically impossible to tell exactly how much snow fell, and if the scoured snow moved nearby, or if perhaps the continued increase in snowfall was in part due to snow scoured from above the sensor and deposited beneath the sonic ranger.

Near the end of this period, another snowfall occurred, depositing 8.4cm of snow in 12 hours between September 28 at 7pm and September 29 at 7am. This snowfall does not seem to be correlated to any changes in temperature or wind speed at JJMC, though there is a large increase in wind speed at AHAB. The maximum wind speed at AHAB during this time period is 28 m/s.

5.2.4 Storm synoptic progression



Average geopotential height at 700mb for September 2004.

For all September days listed, the synoptic charts are geopotential height, precipitable water, and vector wind, all plotted at 700mb. On September 24th, the fourth chart is air temperature. (http://www.cdc.noaa.gov/Composites/Day/)

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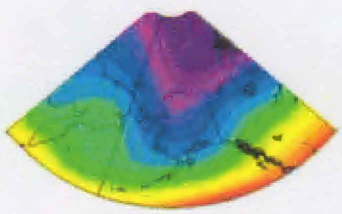
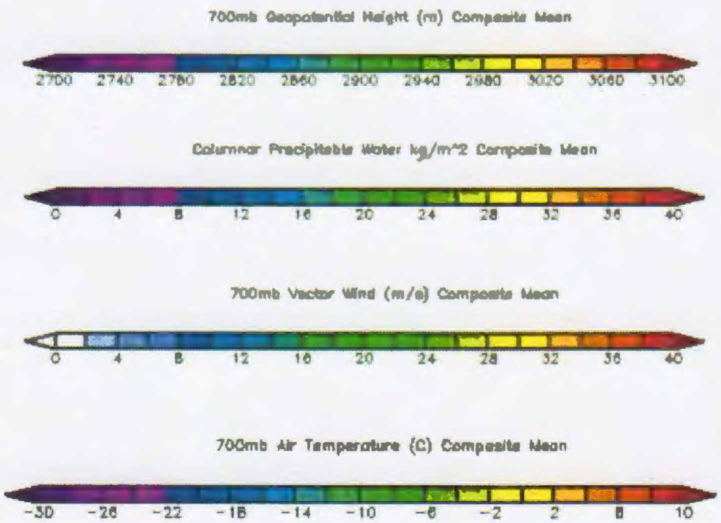
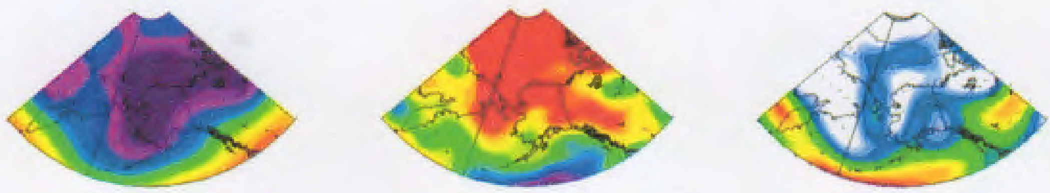
5.2.4 Storm synoptic progression



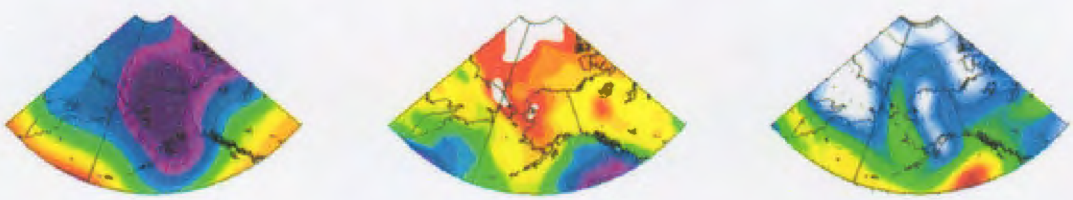
Average geopotential height at 700mb for September 2004.

For all September days listed, the synoptic charts are geopotential height, precipitable water, and vector wind, all plotted at 700mb. On September 24th, the fourth chart is air temperature. (http://www.cdc.noaa.gov/Composites/Day/)

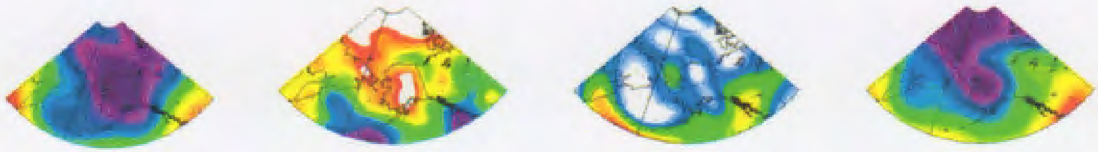




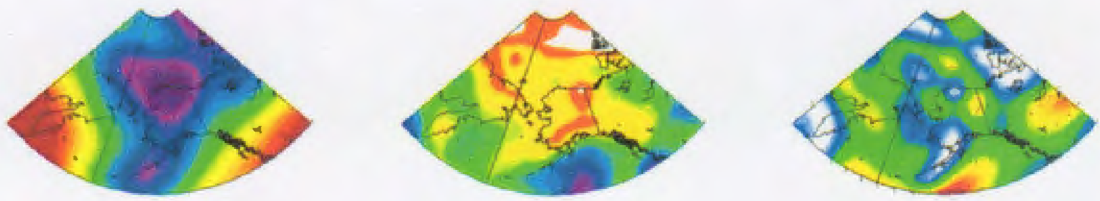
September 22- strong southerly flow combined with high moisture content from the Bering Sea in the S-SE reaches the mountains and releases the moisture in the form of 5.5cm of snow. The flow is most easily seen in the vector wind chart.



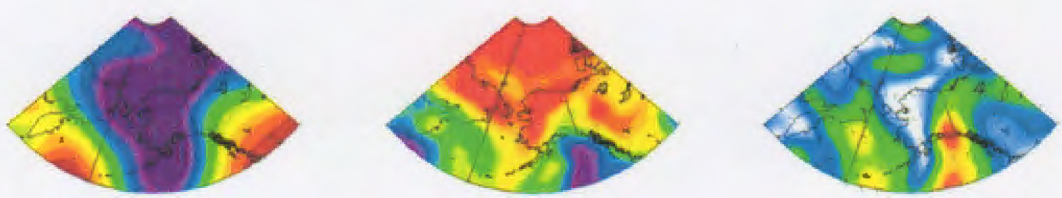
September 23- movement of low further east, flow now more westerly, from the Seward Peninsula and originating from a less moisture-laden air mass. The vector wind chart illustrates this most visibly.



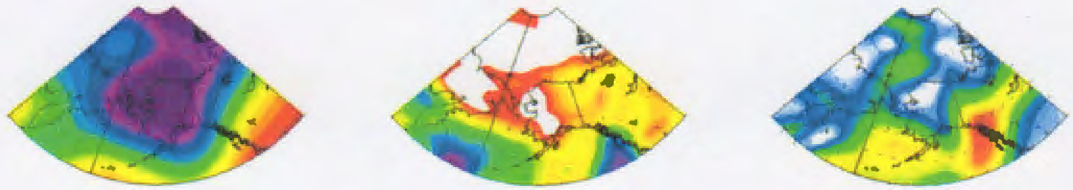
September 24- Cold air advected into the region from north, which the temperature chart indicates. This corresponds with the 11° drop in temperature in the data.



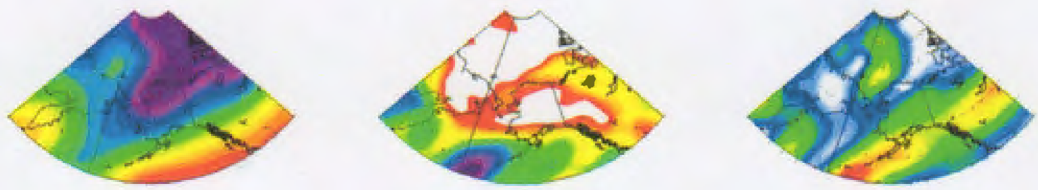
September 25- there is a significant increase in wind speed, still from the west and lacking precipitable moisture. The increase in wind speed corresponds with the snow scour event in which ultimately decreases the snow depth by 12.4cm.



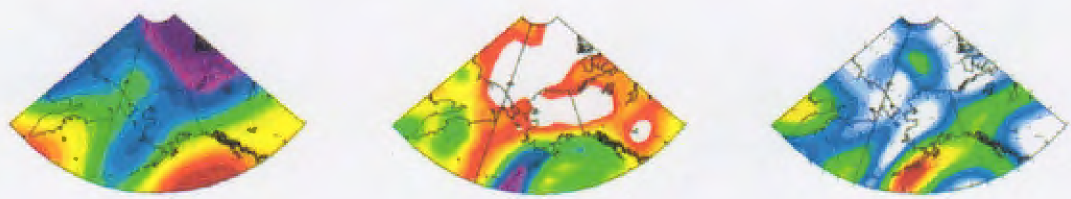
September 26- low pressure system has increased in area, and shifted south, so the flow is more southerly, which generally relieves the air mass of moisture over the Alaska Range. The wind shift brings increased temperatures, and increases the chance of precipitation.



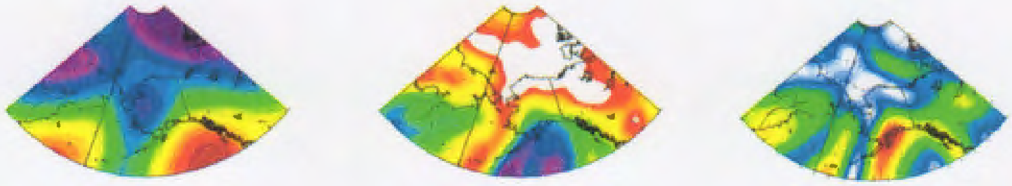
September 27- low strengthens, increasing wind speed and advecting moisture from the west



September 28- low shifts to the north, temperature drops rapidly (15° C) as cold air from the north swings around the low.



September 29- low moves far enough north to allow a north wind to bring moisture from the Beaufort Sea, as illustrated in the vector wind chart, which is orographically lifted and cooled, resulting in the 8.4cm snowfall indicated in the data.



September 30- flow now from the south, fairly moisture free, end of snow and wind event.

5.3 November 2004

The period November 7-27, 2004 is marked by a snowfall event that results in a significant increase in snow depth as well as a decrease in temperature (Fig. 24).

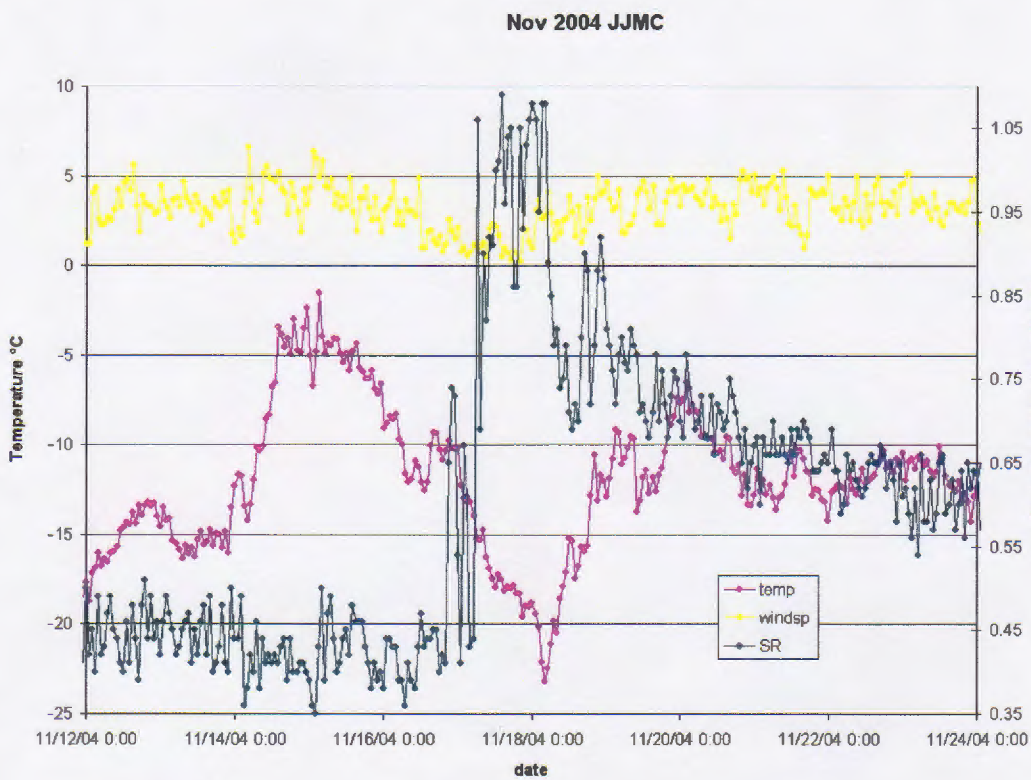


Figure 24: Temperature (°C), wind speed (m/s), and snow depth (cm) for the period November 7-27, 2004.

5.3.1 Wind speed and direction

At AHAB, the dominant wind direction for the period 2004-June 2005 is 86°, while during the period Nov 15-19, the average wind direction at AHAB is 62°. This slight back to the north correlates with the NCEP synoptic charts for the period. At JJMC, the average wind direction for the fall of 2004 is 180°, while for the period November 16-18, the average wind direction is 145°. During this period, the maximum wind speed at AHAB reached 8.4 m/s, which is lower than observed during other snowfall events at AHAB. The JJMC wind speed dropped from a monthly average of 3.2 m/s to an average of 1.3 m/s during the period of greatest initial accumulation, November 16-18.

5.3.2 Temperature

The temperature dropped 13.8° C from -9.4° C to -23.2° C during the initial day and a half of the snowfall event. During the second half of the snowfall event, the temperature rose 16.7° C to -6.5° C. This initial drop in temperature would support the hypothesis that the snowfall was very dry and fluffy, likely made up of spatial plates (Nakaya 1954).

5.3.3 Precipitation

Precipitation, expressed as snow depth, varied during this period and may be broken down into four timeframes:

1) Gradual, steady decrease as event begins (Nov 7-16)

2) Period of rapid accumulation (Nov 17)

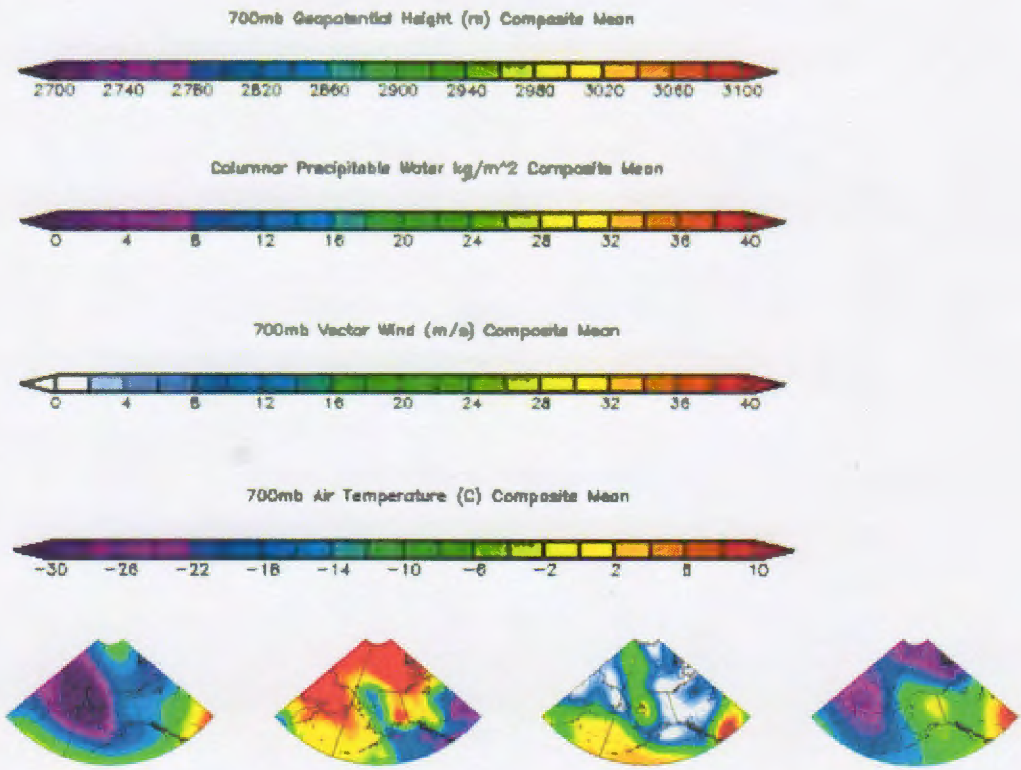
3) Short period of rapid increase (Nov 18)

4) Decrease, initially rapid then decreasing in rate after Nov 22 (Nov 18-28)

The overall pattern for accumulation in November 2004 is slow ablation punctuated by periods of rapid accumulation, such as that occurring around November 17, 2004. The greatest accumulation achieved during this period was 6.9cm over a period of 14 hours (period 2) on the 17th of November, with depth fluctuations between 2 and 4cm between hourly measurements. During the first 9 hours after peak accumulation, 4cm was removed. A second, short duration period of accumulation added a further 2.3cm over the next 9 hours (period 3). The extent of the snow response coupled with the relatively low wind speeds leads to the conclusion that the snow was dry, making it light and fluffy, and thus more easily moved around by even the weak wind during this period. As can be seen from the CDC synoptic charts for 700mb, the pressure gradient on November 16 and 17 is bringing moisture from the Bering Sea in the Yukon Delta region, sweeping in between the Alaska Range and the Brooks Range. The relative humidity during the peak snow accumulation reached into the 90's for a few hours at JJMC, which supports a snow fall event.

5.3.4 Synoptic progression

For all November days listed, the synoptic charts are geopotential height, precipitable water, vector wind, and temperature, all plotted at 700mb. The timing of the plots is 12 hours ahead of the local observations on the glacier, such that the high precipitable water values noted on Nov. 16 correspond to snowfall on the 17th.

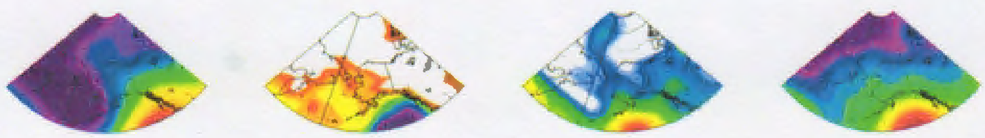


November 15- The flow pattern is dominated by a large low centered over the Chukotka Sea. Air is moved eastward across the Bering towards the Gulf of Alaska coast and then swings rapidly north (a). The air mass is displaced far enough to the south that when it swings around to the north it is forced to transit the Alaska Range which reduces its moisture content (b). Thus the characteristics of this moderate south-southeasterly flow over the McCall vicinity are relatively warm and dry. This is reflected in Fig. 24 as a temperature increase commencing at this time can be seen in the temperature chart. Wind speed (c) and moisture content (d) remain low.

November 16- The Chukotka low has weakened and shifted northward. This allows the easterly component of the flow to intersect Alaska on the west coast, over the Yukon delta region (a). Now the northward shift of air flow does not force a transit of the Alaska Range, which allows the relatively high moisture content to remain intact across the flatter interior (b) and so placing moisture over the McCall vicinity. The temperature changes from increasing to a steady decrease (d). The greater moisture levels combined with lower temperatures initiates the main precipitation event. Winds during this period are very low, allowing accumulation to proceed unhindered (c).

November 17- The south-westerly flow continues to bring moisture from the Bering Sea (a), keeping atmospheric moisture contents high enough (b) to allow a second snowfall episode. During this period the winds begin a slight shift towards the south, giving the short period of temperature increase observed in Fig. 24.

November 18- The flow pattern takes up an initial southerly flow, cutting off the moisture conduit from the Bering Sea, moving around to a west to east orientation across the McCall region (a). This reduces atmospheric moisture content (b) and small pressure gradients correspond with lower wind speeds (c).



November 19- The pattern is similar to that observed for Nov. 18 (a). Moisture content, winds, and temperatures do not show strong change.

5.4 2004-2005 Winter Storms

The period between Dec 15, 2004 and Jan 12, 2005 is some of the stormier weather at McCall between 2003 and 2005 (Fig. 25).

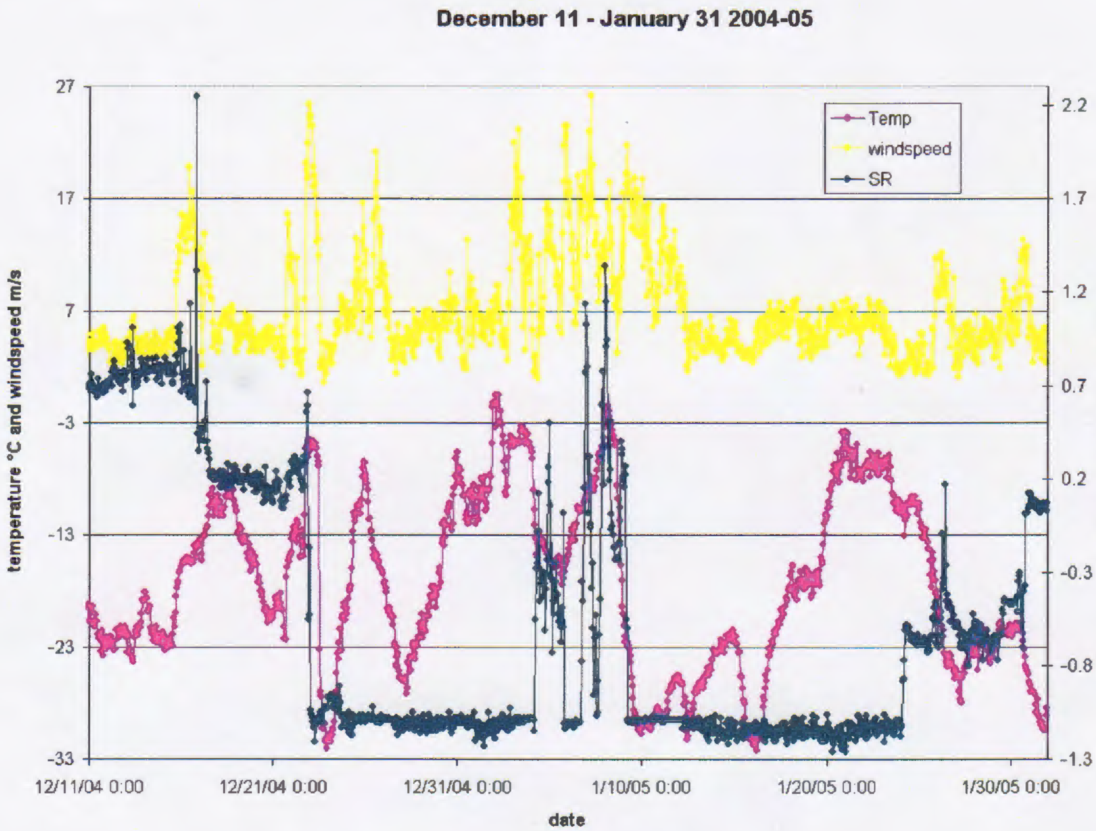


Figure 25: JJMC winds, precipitation, and temperatures December 2004-January 2005

5.4.1 Wind Direction

Wind direction at JJMC on average is around 180°. During this storm, the wind direction shifted to 93° from January 5 to 11th. AHAB wind directions shifted slightly from the average 60° to 89° during the beginning of the windy period after January 3rd. As the temperature is below freezing at AHAB during this event, it is safe to assume that

AHAB experienced riming on the wind sensors, rendering the wind data useless after January 6th.

5.4.2 Wind Speed

Wind speed reached the highest on record at JJMC for all data available. There are four distinct wind events during the period between December 15 and January 11. The first occurs on December 16, reaching a maximum speed of 19.8 m/s. The second wind spike occurs on December 22nd, reaching speeds of 25.4 m/s. The third wind event lasted slightly longer, over the day of December 26th, and reached 21.1 m/s. The last wind event during this period was the strongest and longest lasting, occurring between January 3rd and 11th, and reaching a maximum speed of 26.2 m/s at JJMC. The maximum wind speed reached at AHAB before sensors return blank data was 34.9 m/s on January 4th.

5.4.3 Precipitation

Precipitation, expressed as snow depth, varied during this period and may be broken down in to seven timeframes:

1) Rapid increase then rapid decrease (December 16)

2) Steady decrease (December 17 - 22)

3) Slight increase then rapid decrease (December 22 – 23)

4) Steady (December 23 – January 4)

5) Rapid increase then rapid decrease (January 4 – 6)

6) Rapid increase then rapid decrease (January 6 – 9)

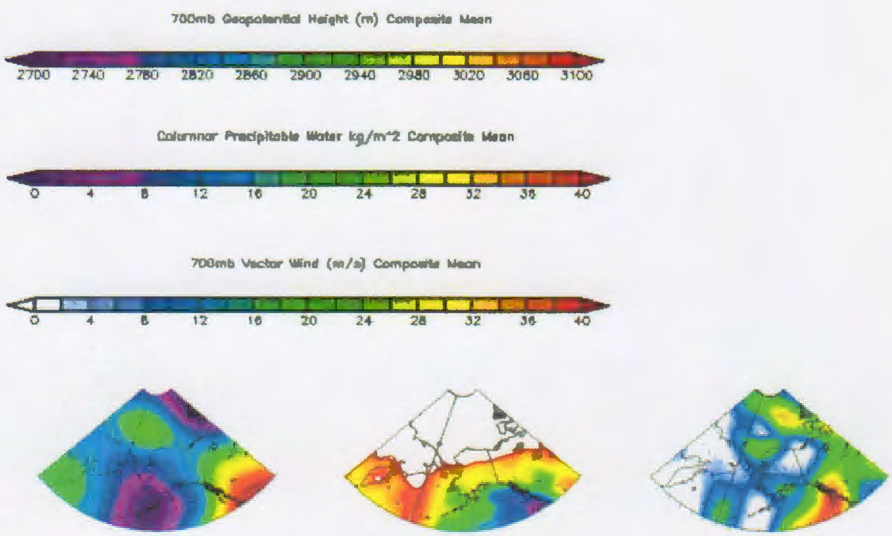
7) Steady (January 9 on)

There must be an ice layer in the snowpack at -1.11 during this storm, because the only time the Sonic ranger record goes below this is at the beginning of the corrected record, on 9/26/2004, when the ranger data goes from its lowest at -1.79 to -.96 in one day. This period of data also includes some of the greatest snowfalls in the record, snowing 2.5cm in one event. During period 1), it snowed 16.4cm in one hour, then strong winds up to 20m/s scoured away 20.4cm. Period 3) was marked by a small increase of 5 cm followed by a decrease of 18.7cm in under 12 hours. This decrease was accompanied by a wind speed spike of 25 m/s, and a temperature drop of 28° C. The sustained high winds throughout periods 5) and 6) accompanied the accumulation and direct loss of 6.5cm in 24 hours, then 22cm within the next 24 hours, and 23cm within the 48 hours following. Wind speeds during this period reached 26 m/s, and averaged 13 m/s.

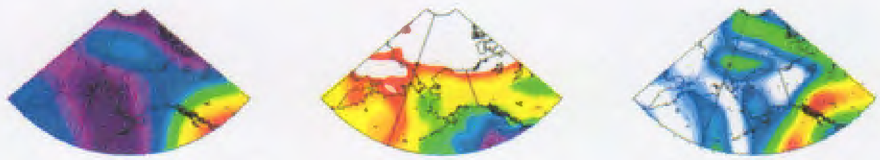
5.4.4 Synoptic progression

Figure 26: Average geopotential height at 700mb for Oct-Dec 2004 and Jan-April 2005

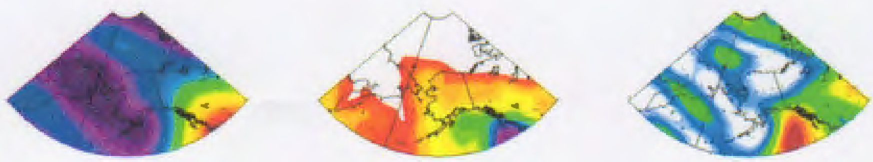
For the days December 16-23 and January 4-10, the synoptic charts are geopotential height, precipitable water, and vector wind, all plotted at 700mb. For days December 24-January 3, the synoptic charts are only geopotential height plotted at 700mb. (http://www.cdc.noaa.gov/Composites/Day/)



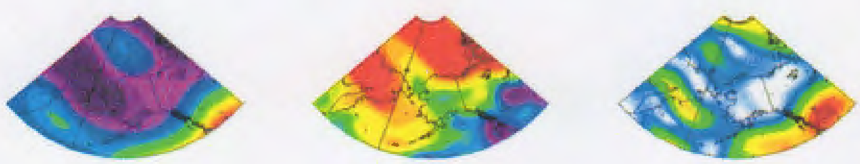
December 16- From these charts, it looks as if the precipitation for this day may have been locally influenced. The low in the Beaufort Sea may have brought wind from the north, possibly picking up moisture from the ocean, and dropping it on the Brooks Range.



December 17- The pressure gradient is decreasing, winds are decreasing, and the Aleutian low is backing Northwest.

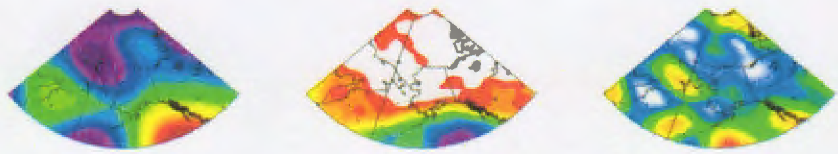


December 18- The low has moved further north, winds are slight and from the south.

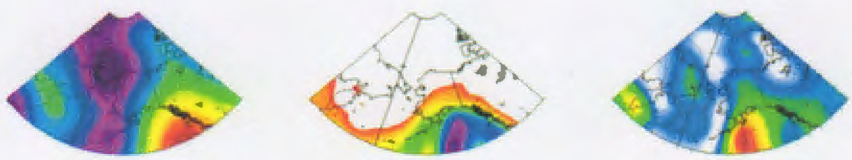


December 19- The low has moved still further north, a fairly steady system.

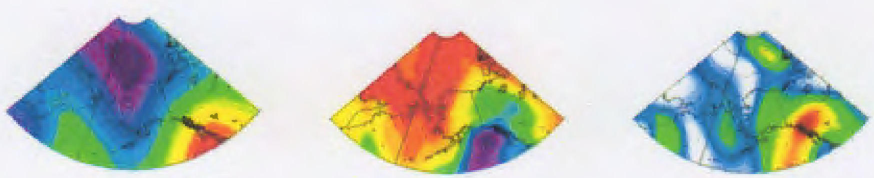
December 20- Low is even further north, starting to bring winds from the Yukon delta area across the state.



December 21- low has moved further north, and a strong pressure gradient, including both a low and a high has developed to the south of the state. Winds are increasing across the state.

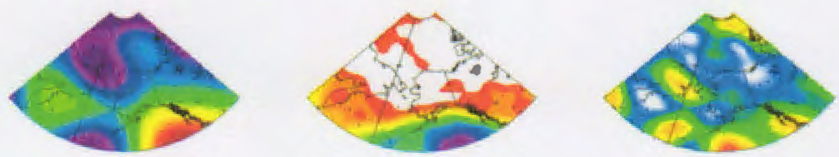


December 22- The lows are starting to connect, and the pressure gradient is fairly strong, allowing for an increase in wind speed, in a southwest direction, bringing moisture across the state.

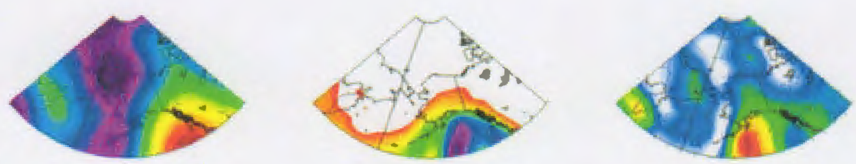


December 23- Pressure gradient has decreased somewhat, and the low has moved further north and to the east. Still higher wind speeds, due to the location of the pressure gradient.

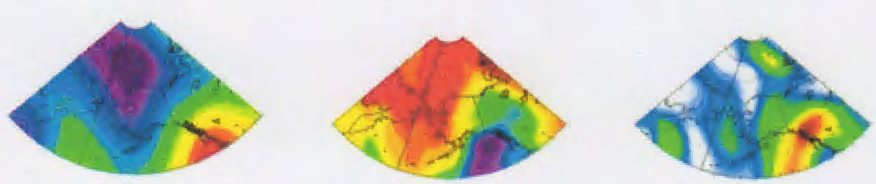
December 20- Low is even further north, starting to bring winds from the Yukon delta area across the state.



December 21- low has moved further north, and a strong pressure gradient, including both a low and a high has developed to the south of the state. Winds are increasing across the state.



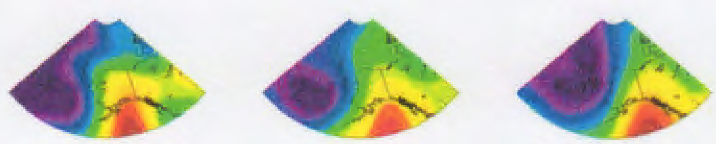
December 22- The lows are starting to connect, and the pressure gradient is fairly strong, allowing for an increase in wind speed, in a southwest direction, bringing moisture across the state.



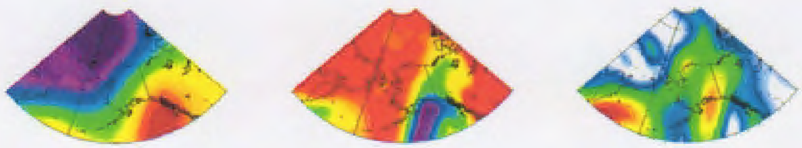
December 23- Pressure gradient has decreased somewhat, and the low has moved further north and to the east. Still higher wind speeds, due to the location of the pressure gradient.

December 24-27- Position of low to the north of Alaska, gradient crosses over McCall area, and the temperature increases 25 degrees the 24^{th} and 25^{th}, and decreases 20 degrees the next two days, while the wind speed stays fairly high. No moisture is received on the glacier. (Only geopotential height is shown for these days)

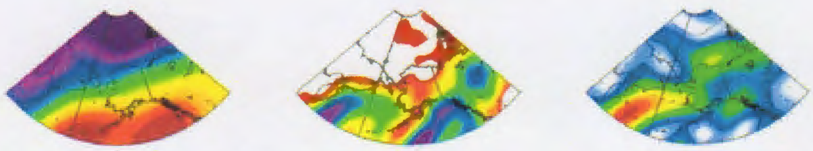
December 28-31- High pressure system moves across Alaska. Wind speeds are low, and temperature increases 20 degrees over four days. (Only geopotential height is shown for these days)



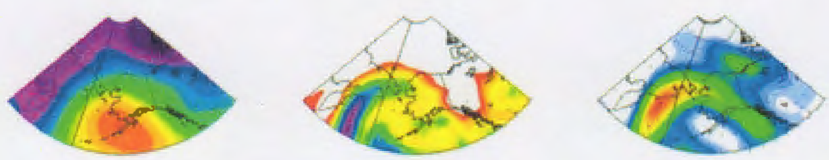
January 1-3- Low pressure system to the west of Alaska, pressure gradient increases. Wind speeds increase on the 3^{rd}, as the pressure gradient is strongest over the McCall area. (Only geopotential height is shown for these days)



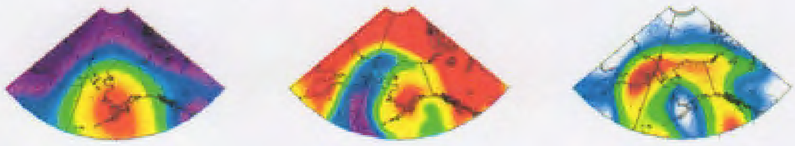
January 4- High winds from the southwest bring moisture-laden air to the Brooks Range, wind speeds are high and there is an increase in snowfall (Fig. 25).



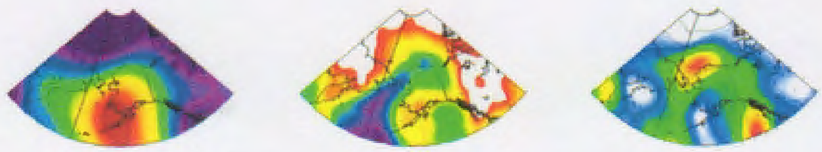
January 5- Low pressure system shifts to the north, winds are still strong through the pressure gradient band, the accumulated snow from the previous day is scoured away by high winds.



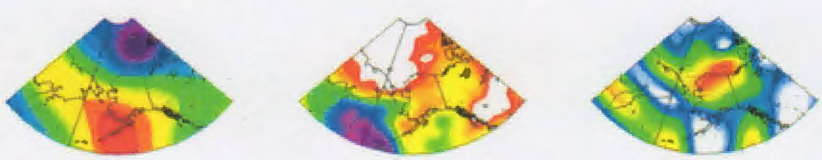
January 6- high pressure system over the Aleutians pushes the low pressure far enough north that the gradient winds come from the north, bringing moisture over McCall glacier, dropping 20cm of snow throughout the fairly windy day.



January 7- Strong pressure gradient with the high centered on the Alaska Peninsula increases the wind speeds at McCall, scouring away the 20cm of snow within the first half of the day and returning the 20cm by the end of the day.



January 8- Pressure gradient has decreased slightly, though weaker winds are generally from the same direction, bringing a few small flurries.



January 9- Pressure gradient strongly decreased, though the path of the strongest gradient lies directly across McCall, and the snow is scoured away completely. Temperatures are very low.

January 10- Winds are still strong, as the pressure gradient increases. Wind is from the north over McCall. Temperatures stay low.

Chapter 6 Discussions and Conclusions

6.1 Phase I: temperature climatology

McCall glacier, as well as Chamberlin glacier and the immediate surrounding area, tend to have most similar weather patterns to nearby stations that are near the coast, though the weather in the EBR is more closely related to the weather of stations that were either slightly inland or further east than Barrow or Barter Island. While the climatology of Lake Peters is slightly more biased to the coastal stations, this is likely due to its elevation and location in the foothills. It was found that the McCall glacier is generally a swing-site, and the climatology of the region often was linked most closely to the Beaufort coast, though on some occasions, was more closely related to the Mackenzie River Delta, and on other occasions, most related to the Interior (Fig. 11). The location of McCall Glacier within the Brooks Range, between these three climate zones, allows for its greater range of synoptic influence.

6.2 Phase II: synoptic

Some of the broadest trends indicate that, on average, precipitation events in which significant snowfall is received on McCall Glacier are typically accompanied by winds from the southwest or north-northwest. Air upwind of McCall in these directions have moisture sources to draw on and are not blocked by mountain ranges other than the Brooks Range. Air flowing from the southwest is funneled through the lowland region between the Brooks Range to the north and the Alaska Range to the south, which reduces moisture loss due to orographic lift. The moisture source region in this case is the

Bering/southern Chukchi Seas. Air flowing from the north-northwest is moving in from the Beaufort Sea moisture source region and is again relatively unaffected by orographic moisture loss. It is speculated that flow from due north will arrive at McCall with potentially higher moisture content than air from the northwest because the ocean is relatively close and the air mass spends less time over land.

Strong winds (defined as >8-15 m/s depending on the weather station in question) are generally from the southwest or west, though occasionally from the north. This is due to a common synoptic situation that develops Alaska in which a low is situated to the north and a high to the south, with a resultant strong pressure gradient that favors southwest winds (Fig. 27).

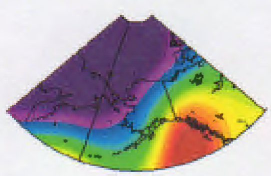


Figure 27: Strong wind situation.

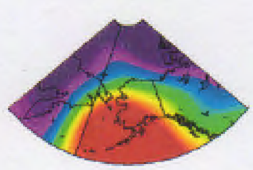


Figure 28: Strong wind and 20cm snowfall situation (moisture from north)

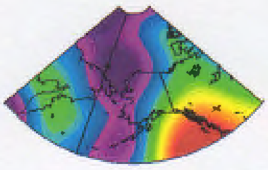


Figure 29: Strong wind situation

The broad objective of the local synoptic study was to determine the general synoptic controls influencing snow depth on McCall Glacier and how they have changed over time. Specific questions are answered in brief below:

- What is the prevalence of summer snow events?

They occur occasionally throughout the summer, once a month is average. Most events are comprised of an inch or two of snow that melts within a week, though occasionally, a summer snow will effectively end the melt season early, sometimes up to as much as a month before average.

- What does a typical storm event look like on McCall Glacier?

Often, storms either come from the north-northwest, or from the southwest, though occasional storms from further east or further west have been known to occur.

- How often do wind scour events, which remove snow from the glacier surface, occur?

Wind scour events occur at least once or twice a month, though they are not necessarily strong enough to remove great quantities of snow, often the snow is light enough to be moved around by wind events.

- For the period of record, what is the frequency and magnitude of snowfall events?

Snowfall occurs at least once a month, and as often as four times, with the magnitude of snowfalls often being between 5mm and 15mm, though light dustings are frequent and hard to measure.

- What is the main source of moisture for the glaciers of the eastern Brooks Range?

Most moisture of the EBR glaciers comes from either the north-northwest (Beaufort Sea) or the southwest (the Pacific Ocean) when winds are strong enough to bring the moisture over the Brooks to McCall Glacier.

- Is there a favored direction from which storms come?

Many of the strong wind events come from the Northeast, though a few are from the east or northwest.

- What is the main snow depth control for McCall glacier: snowfall or wind scour?

Snowfall and wind scour play an equally important role in the snow depth of McCall glacier. Little snow falls and winds are often enough that often a new snow is blown away before it has a chance to compress enough to stay.

The McCall glacier is an excellent long-term research area with a solid history of research that should be utilized and continued for the greater knowledge of the effects of climate change on our arctic world.

References

Alexander, M. J. *McCall Glacier Project.* Alaska: Geophysical Institute, University of Alaska Fairbanks, 1974. Videorecording.

Arendt, A., and Sharp, M. "Energy Balance measurements on a Canadian high Arctic glacier and their implications for mass balance modeling." *Interactions Between the Cryosphere, Climate, and Greenhouse Gases (proceedings of IUGG 99 Symposium HS2, Birmingham, July 1999)* IASH Publ. No. 256 (1999): 165-172. Print.

Arnold, N. "Investigating the sensitivity of glacier mass-balance/elevation profiles to changing meteorological conditions: Model experiments for Haut Glacier D'Arolla, Valais, Switzerland." *Arctic, Antarctic, and Alpine Research* 37.2 (2005): 139-145. Print.

Atkinson, D.E. *Topoclimate modeling of surface climate temperature in the Canadian arctic archipelago.* Ottowa: University of Ottowa, 2000. Print.

Balascio, N., Kaufman, D., Briner, J., and Manley, W. "Late Pleistocene glacial geology of the Okpilak-Kongakut Rivers region, Northeastern Brooks Range, Alaska." *Arctic, Antarctic, and Alpine Research* 37.4 (2005): 416-424. Print.

Benson, C. S. "The Seasonal Snow Cover of Arctic Alaska." *Arctic Institute of North America* Research Paper no. 51 (1969). Print.

Bitz, C.M. and Battisti, D.S. "Interannual to decadal variability in climate and the glacier mass balance in Washington, Western Canada, and Alaska." *Journal of Climate* 12.11 (1999): 3181-3196. Print.

Bøggild, C. E., Reeh, N., and Oerter, H. "Modelling ablation and mass-balance sensitivity to climate change of Storstrømmen, Northeast Greenland." *Global and Planetary Change* No. 9 (1994): 79-90. Print.

Boon, S. and Sharp, M.J. "Impact of High-Latitude Chinook Events on Arctic Glacier Hydrology." *58th Eastern Snow Conference, Ottowa, Ontario, Canada* (2001): 97-106. Print.

Brown, J. *Soils of the Northern Brooks Range, Alaska.* New Jersey: Rutgers University, 1962. Print.

Calkin, P. E. "Holocene glaciation of Alaska (and adjoining Yukon Territory, Canada)." *Quaternary Science Reviews* Vol. 7 (1988): 159-184. Print.

Calkin, P.E., Ellis, J.M., Haworth, L.A., and Burns, P.E. "Cirque glacier regime and neoglaciation, Brooks Range, Alaska." *Zeitschrift fur Gletscherkunde und Glazialgeologie* Band 21 (1985): 371-378. Print.

Climate Data Center. "Climate Data Center Images." *NOAA-ESRL Physical Sciences Division*. Boulder Colorado. <http://www.cdc.noaa.gov/>. Web. August 2009.

Cogley, J.G., and McCann, S.B. "An exceptional storm and it effects in the Canadian High Arctic." *Arctic and Alpine Research* Vol. 8 (1976): 105-110. Print.

de Percin, F. *The summer climate of the lake Peters area, Brooks Range, Alaska.* Research Study Report RER-25 Environmental Protection Research Division, Quartermaster Corps. 1959. Print.

Dissing, D. *Radiation Climatology of Alaska*. Alaska: University of Alaska, Fairbanks, 1997. Print.

Dorrer, E., and Wendler, G. "Climatological and Photogrammetric speculations on mass-balance changes of McCall Glacier, Brooks Range, Alaska." *Journal of Glaciology* 17.77 (1976): 479-490. Print.

Dowdeswell, J.A. "Glaciers in the High Arctic and recent environmental change." *Philosophical Transactions of the Royal Society of London* Vol. 352 (1995): 321-334. Print.

Fahl, C. B. *Some Relationships Between Glaciers and Climate in Alaska*. Alaska: University of Alaska, Fairbanks, 1973. Print.

Francou, B., Vuille, M., Wagnon, P., Mendoza, J., and Sicart, J. "Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16S." *Journal of Geophysical Research* 108.D5 (2003): 4154-4166. Print.

Geographic Information Network of Alaska. "Image of North Slope, Alaska." *University of Alaska - GINA*. 2008. <http://www.gina.alaska.edu/>. Web. August 2009.

Hannah, D., Gurnell, A., and McGregor, G. "Identifying links between large-scale atmospheric circulation and local glacier ablation climates in the French Pyrenees. Interactions between the cryosphere, climate, and greenhouse gases." *Proceedings of IUGG 99 Symposium HS2, Birmingham, July 1999.* IAHS Publication no. 256 (1999): 155-164. Print.

Hartmann, B. and Wendler, G. "The significance of the 1976 Pacific Climate Shift in the climatology of Alaska." *Journal of Climate* Vol. 18 (2005): 4824-4839. Print.

Hastenrath, S., and Ames, A. "Diagnosing the imbalance of Yanamarey Glacier in the Cordillera Blanca of Peru." *Journal of Geophysical Research* 100.D3 March (1995): 5105-5112. Print.

Hobbie, J. E. *Limnological Cycles and Primary Productivity of Two lakes in the Alaskan Arctic.* Indiana: Indiana University, 1962. Print.

Hobbie, J. E. Original Lake Peters meteorological data from periods between July, 1958 and August, 1961. [Original papers]. John Hobbie [producer]. Woods Hole, MA. 2007.

Hock, R. "Temperature index melt modeling in mountain areas." *Journal of Hydrology* Vol. 282 (2003): 104-115. Print.

Hodgkins, R. "Seasonal evolution of meltwater generation, storage, and discharge at a non-temperate glacier in Svalbard." *Hydrological Processes* Vol. 15 (2001): 441-460. Print.

Holmes, G. W. et al. *Preliminary Report of the Mt. Chamberlin- Barter Island, Alaska, Project.* Cambridge: Air Force Cambridge Research Center, 1958. Print.

Kaltenbock, R. and Obleitner, F. "On a Low Cloud Phenomenon at the Breidamerkurjokull Glacier, Iceland." *Boundary Layer Meteorology* Vol. 92 (1999): 145-162. Print.

Kelly, P.M., Jones, P.D., Sear, C.B., Cherry, B.S.G., and Tavakol, R.K. "Variations in surface air temperatures: Part 2, Arctic Regions, 1881-1980." *Monthly Weather Review* 110.2 (1982): 71-83. Print.

Klok, E.J., Nolan, M., Van Den Broeke, M.R. "Analysis of meteorological data and the surface energy balance of McCall glacier, Alaska, USA." *Journal of Glaciology* 51.174 (2005): 451-461. Print.

LaChapelle, E. *The Blue Glacier Project, 1959 and 1960. Final Report, Office of Naval Research Contract 477 (18) (NR 307-244).* Washington: Dept of Meteorology and Climatology, University of Washington, December 1960. Print.

Larsson, P. *Meteorological Observations on the Chamberlin Glacier; Brooks Range, Arctic Alaska, Summer 1958.* Montreal: McGill University, April 1960. Print.

Laumann, T. and Reeh, N. "Sensitivity to climate change of the mass balance of glaciers in southern Norway." *Journal of Glaciology* 39.133 (1993): 656-665. Print.

Letreguilly, A. "Relation between the mass balance of western Canadian mountain glaciers and meteorological data." *Journal of Glaciology* 34.16 (1988): 11-18. Print.

Ling, F., and Zhang, T. "Modeling the effect of variations in snowpack-disappearance date on surface-energy balance on the Alaskan North Slope." *Arctic, Antarctic, and Alpine Research* 37.4 (2005): 483-489. Print.

MacDonald, T.H. "Some characteristics of the Eppley pyrheliometer." *Monthly Weather Review* 79.8 August 1951: 153-159. Print.

Mason, R. W. "The McCall Glacier project and its logistics." *Arctic*12.2 June 1959: 77-97. Print.

Mayo, L.R. and March, R.S. "Air temperature and precipitation at Wolverine Glacier, Alaska; glacier growth in a warmer, wetter climate." *Annals of Glaciology* Vol. 14 (1990): 191-194. Print.

McCabe, G. and Fountain, A. "Relations between atmospheric circulation and mass balance of South Cascade Glacier, Washington, USA." *Arctic and Alpine Research* 27.3 (1995): 226-233. Print.

Meier, M. F. "Hydraulics and hydrology of glaciers." In *The Role of Snow and Ice in Hydrology*. International Association of Hydrological Sciences. Vol. 107 (1973): 353–369. Print.

Nakanishi, S., Curtis, J., and Wendler, G. "The influence of increased jet airline traffic on the amount of high level cloudiness in Alaska." *Theoretical Applications of Climatology* Vol. 68 (2001): 197-205. Print.

Nakaya, U. *Snow Crystals*. Cambridge: Harvard University Press, 1954. Print.

National Academy of Sciences. "The International Geophysical Year." *National Academy of Sciences*. 2005. <http://www.nas.edu/history/igy/>. Web. August 2009.

NSIDC/WDC for Glaciology, Boulder, compiler. 2002, updated 2007. *Glacier photograph collection.* Boulder, Colorado USA: National Snow and Ice Data Center/World Data Center for Glaciology. Digital media

Nolan, M. "McCall Glacier." *University of Alaska Fairbanks.* 2003. <http://www.uaf.edu/water/faculty/nolan/glaciers/McCall/index.htm >. Web. August 2009.

Nolan, M. McCall Glacier raw data 2003-2005. [Computer file.] Fairbanks, AK. Matt Nolan [producer]. 2005.

Oerlemans, J. and Hoogendoorn, N.C. "Mass balance gradients and climatic change." *Journal of Glaciology* 35.121 (1989): 399-405. Print.

Oerlemans, J. and Klok, E. "Energy balance of a glacier surface: Analysis of automatic weather station data from the Morteratschgletscher, Switzerland." *Arctic, Antarctic, and Alpine Research* 34.4 (2002): 477-485. Print.

Ohmura, A. "Experimental studies on glacier climatology- especially for the melt-climate relationships." Glaciers- Proceedings of workshop seminar, University of British Columbia, Sept 24 and 25, 1970, Canadian National Committee for The International Hydrological Decade, Ottowa, 37-38. Print.

Ohmura, A. "Physical Basis for the temperature-based melt-index method." *Journal of Applied Meteorology* Vol. 40 April 2001: 753-761. Print.

Orvig, S. Ed. *McCall Glacier, Alaska, Meteorological Observations 1957-1958.* Calgary: Arctic Institute of North America, 1961. Print.

Orvig, S. and Mason, R. W. "Ice temperatures and heat flux McCall Glacier, Alaska." *General assembly of Berkeley, August, 1963.* IASH Publ. No. 61 (1963): 181-187. Print.

Pattyn, F., Nolan, M., Rabus, B., Takahashi, S. "Localized basal motion of a polythermal Arctic glacier: McCall Glacier, Alaska, USA." *Annals of Glaciology* Vol. 40 (2005): 47-51. Print.

Pelto, M. "Time-series analysis of mass balance and local climatic records from four northwestern North American glaciers." *Snow Cover and Glacier Variations.* IASH Publication no. 183 (1989): 95-102. Print.

Przybylak, R. *Variability of Air Temperature and Atmospheric Precipitation in the Arctic.* Norwell, MA: Kluwer Academic Publishers, 2002. Print.

Rabus, B. T. *The Mass Balance and the Flow of a Polythermal Glacier, McCall Glacier, Brooks Range, Alaska.* Alaska: University of Alaska, Fairbanks, 1997. Print.

Rabus, B.T. and Echelmeyer, K.A. "Increase of 10m ice temperature: climate warming or glacier thinning?" *Journal of Glaciology* 48. 161 (2002): 279-286. Print.

Rabus, B.T. and Echelmeyer, K.A. "The mass balance of McCall Glacier, Brooks Range, Alaska, USA; its regional relevance and implications for climate change in the Arctic." *Journal of Glaciology* 44.147 (1998): 333-351. Print.

Rabus, B., Echelmeyer, K., Trabant, D., and Benson, C. "Recent changes of McCall glacier, Alaska." *Annals of Glaciology* Vol. 21 (1995): 231-237. Print.

Radok, U. and Watts, D. "A synoptic background to glacier variations of Heard Island." *Snow and Ice Symposium, Moscow, August, 1971* IASH Publ. No. 104 (1975): 42-56. Print.

Rainwater, F.M. and Guy, H.P. *Some observations on the hydrochemistry and sedimentation of the Chamberlin Glacier area, Alaska.* Reston, VA: US Geological Survey Professional Paper 414-C, 1961. Print.

Scherrer, S. C. and Appenzeller, C. "Swiss Alpine snow variability and its links to large scale flow patterns." *ICAM/MAP Brig (CH) Meeting extended abstract proceedings* (2003): 567-570. Print.

Singh, P., Haritashya, U., and Kumar, N. "Meteorological study for Gangotri Glacier and its comparison with other high altitude meteorological stations in central Himalayan region." *Nordic Hydrology* 38.1 (2007): 59-77. Print.

Trabant, D. C. and Mayo, L. R. "Estimation and effects of internal accumulation on five glaciers in Alaska." *Annals of Glaciology* Vol. 6 (1985): 113-117. Print.

Truffer, M. "The basal speed of valley glaciers: an inverse approach." *Journal of Glaciology* 50.169 (2004): 236-242. Print.

van den Broeke, M.R. "Momentum, heat, and moisture budgets of the katabatic wind layer over a midlatitude glacier in summer." *Journal of Applied Meteorology* 36.6 (1997): 763-774. Print.

van den Broeke, M.R. "Structure and diurnal variation of the atmospheric boundary layer over a mid-latitude glacier in summer." *Boundary-Layer Meteorology* Vol. 83 (1997): 183-205. Print.

Weller, G. and Bowling, S.A., Eds. *Climate of the Arctic. 24th Alaska Science Conference, Fairbanks, AK, August 15-17, 1973.* Alaska: Geophysical Institute, University of Alaska, Fairbanks, 1975. Print.

Weller, G., Nolan, M., Wendler, G., Benson, C., Echelmeyer, K., and Unterstiener, N. "Fifty Years of McCall Glacier Research: From the International Geophysical Year 1957-58 to the International Polar Year 2007-08." *Arctic* 60.1 March 2007: 101-110. Print.

Weller, G., Trabant, D., and Benson, C. "Physical characteristics of the McCall Glacier, Brooks Range, Alaska." *Snow and Ice Symposium, Moscow, August, 1971.* IASH Publ. No. 104 (1975): 88-91. Print.

Weller, G. and Wendler, G. "Energy budgets over various types of terrain in polar regions." *Annals of Glaciology* Vol. 14 (1990): 311-314. Print.

Wendler, G. *Studies on the McCall Glacier, Brooks Range, Alaska*. Alaska: Geophysical Institute, University of Alaska, Fairbanks, 1970. Print.

Wendler, G., Fahl, C., and Corbin, S. "Mass balance studies on McCall Glacier, Brooks Range, Alaska." *Arctic and Alpine Research* 4.3 (1972): 211-222. Print.

Wendler, G., Fahl, C., and Corbin, S. "Mass balance studies on McCall Glacier, Brooks Range, Alaska." *Proceedings of the Moscow Snow and Ice Symposium, August 1971.* IAHS-AISH Publ. No. 104 (1975): 197-201. Print.

Wendler, G. and Ishikawa, N. "The combined heat, ice, and water balance of McCall Glacier, Alaska: a contribution to the International Hydrological Decade." *Journal of Glaciology* 13.68 (1974): 227-241. Print.

Wendler, G., and Ishikawa, N. "The Effect of slope, exposure, and mountain screening on the solar radiation of McCall glacier, Alaska: a contribution to the International Hydrological Decade." *Journal of Glaciology* 13.68 (1974): 213-226. Print.

Wendler, G., Ishikawa, N., and Streten, N. "The climate of the McCall Glacier, Brooks Range, Alaska, in relation to its geographical setting." *Arctic and Alpine Research* 6.3 (1974): 307-318. Print.

Woertz, B.B. and Hand, I.F. "The characteristics of the Eppley pyrheliometer." *Monthly Weather Review* 69.5 May 1941: 146-148. Print.

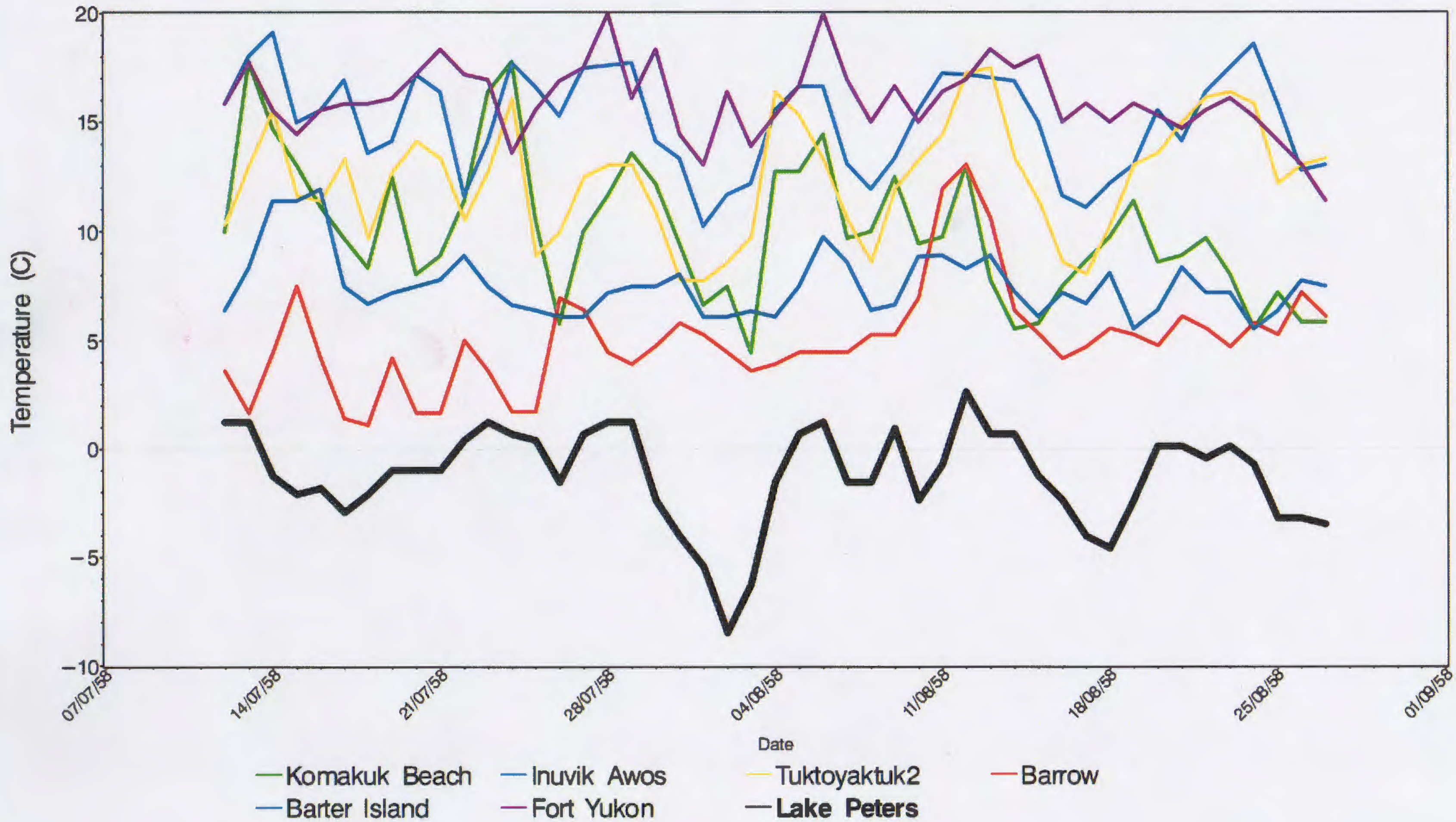
Wolfe, P.W. *Hydrometeorological investigation on a small valley glacier in the Sawtooth Range, Ellesmere Island, Northwest Territories.* Waterloo, Ontario: Wilfrid Laurier University, 1995. Print.

Yarnal, B. "Relationships between synoptic scale atmospheric circulation and glacier mass balance in south-western Canada during the International Hydrological Decade, 1965-1974." *Journal of Glaciology* 30.105 (1984): 188-198. Print.

Yarnal, B. "Synoptic-Scale Atmospheric Circulation over British Columbia in Relation to the Mass Balance of Sentinel Glacier." *Annals of the Association of American Geographers* 74.3 (1984): 375-392. Print.

Appendices

Appendix 1: Average Daily Temperature plots for all available data from July 1958 – September 1961 including McCall Glacier, Lake Peters, Tuktoyaktuk, Komakuk Beach, Barter Island, Barrow, Inuvik, and Fort Yukon.


Temperature (C)
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15
10
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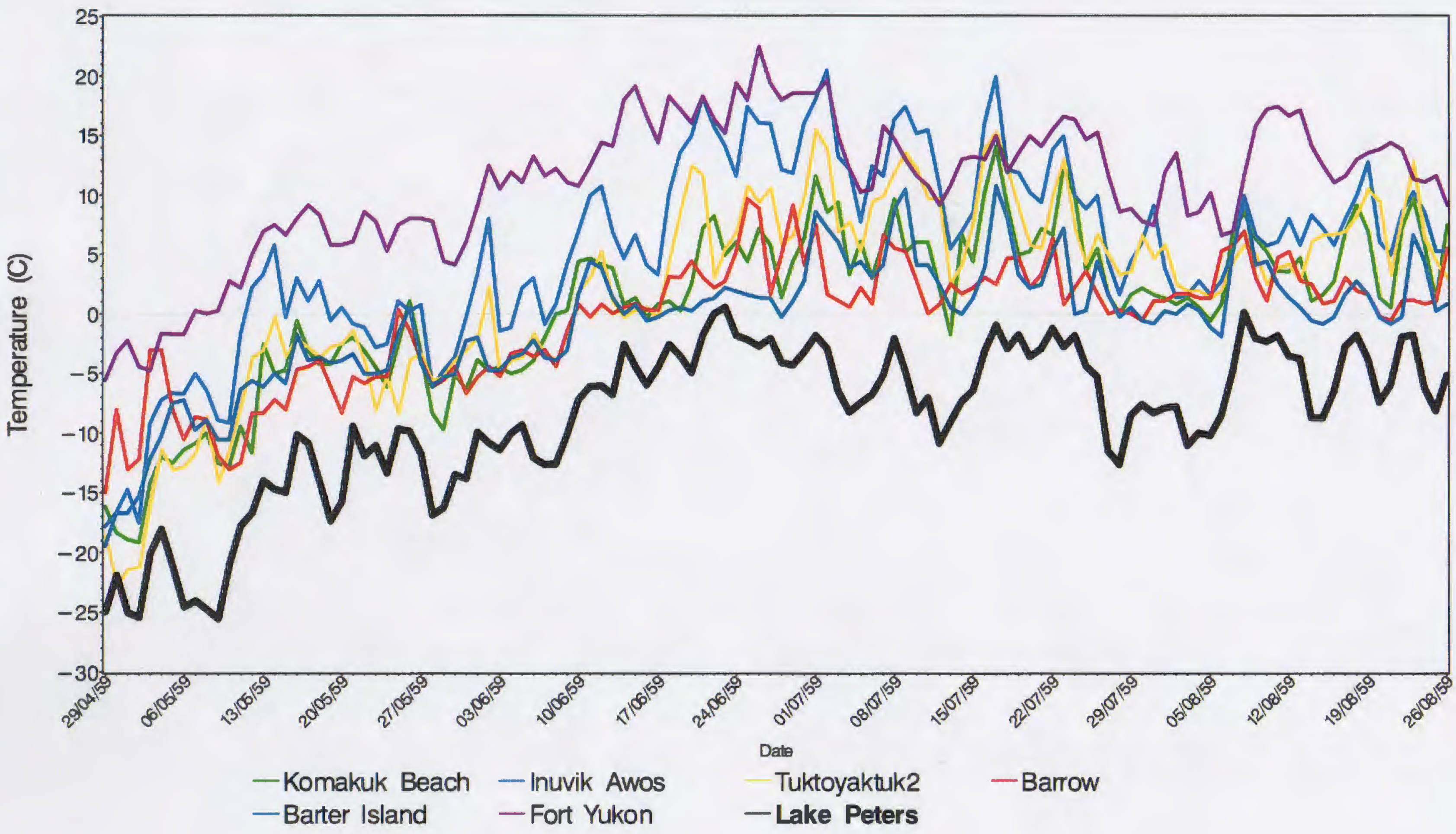
−5
−10
07/07/58
14/07/58
21/07/58
28/07/58
04/08/58
11/08/58
18/08/58
25/08/58
01/09/58
Date
Komakuk Beach
Inuvik Awos
Tuktoyaktuk2
Barrow
Barter Island
Fort Yukon
Lake Peters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20
15
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−15
−20
−25
−30
29/04/59
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27/05/59
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10/06/59
17/06/59
24/06/59
01/07/59
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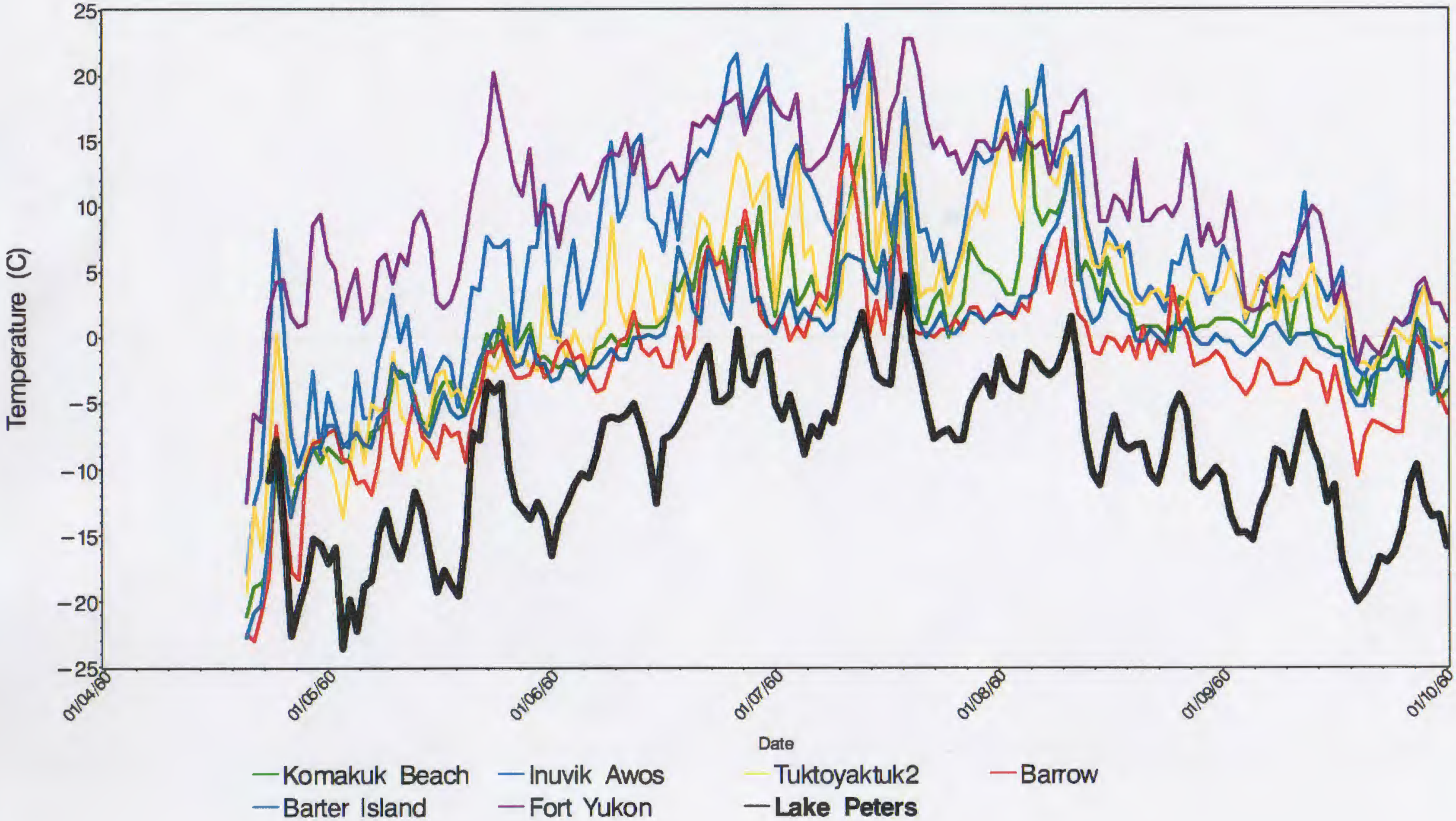
15/07/59
22/07/59
29/07/59
05/08/59
12/08/59
19/08/59
26/08/59
Date
Komakuk Beach
Inuvik Awos
Tuktoyaktuk2
Barrow
Barter Island
Fort Yukon
Lake Peters



Temperature (C)
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01/05/60
01/06/60
01/07/60
01/08/60
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Date
Komakuk Beach
Inuvik Awos
Tuktoyaktuk2
Barrow
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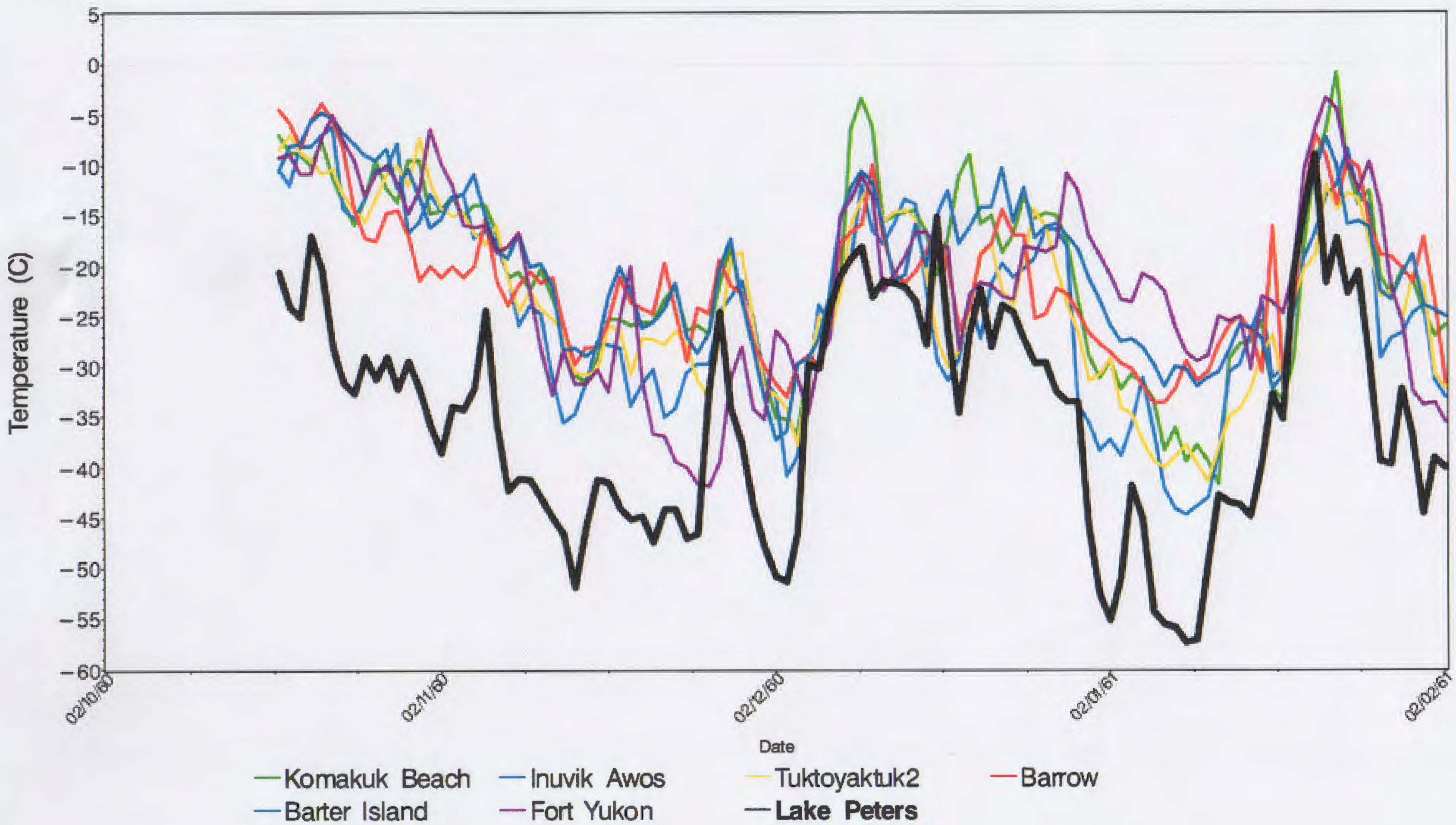
Fort Yukon
Lake Peters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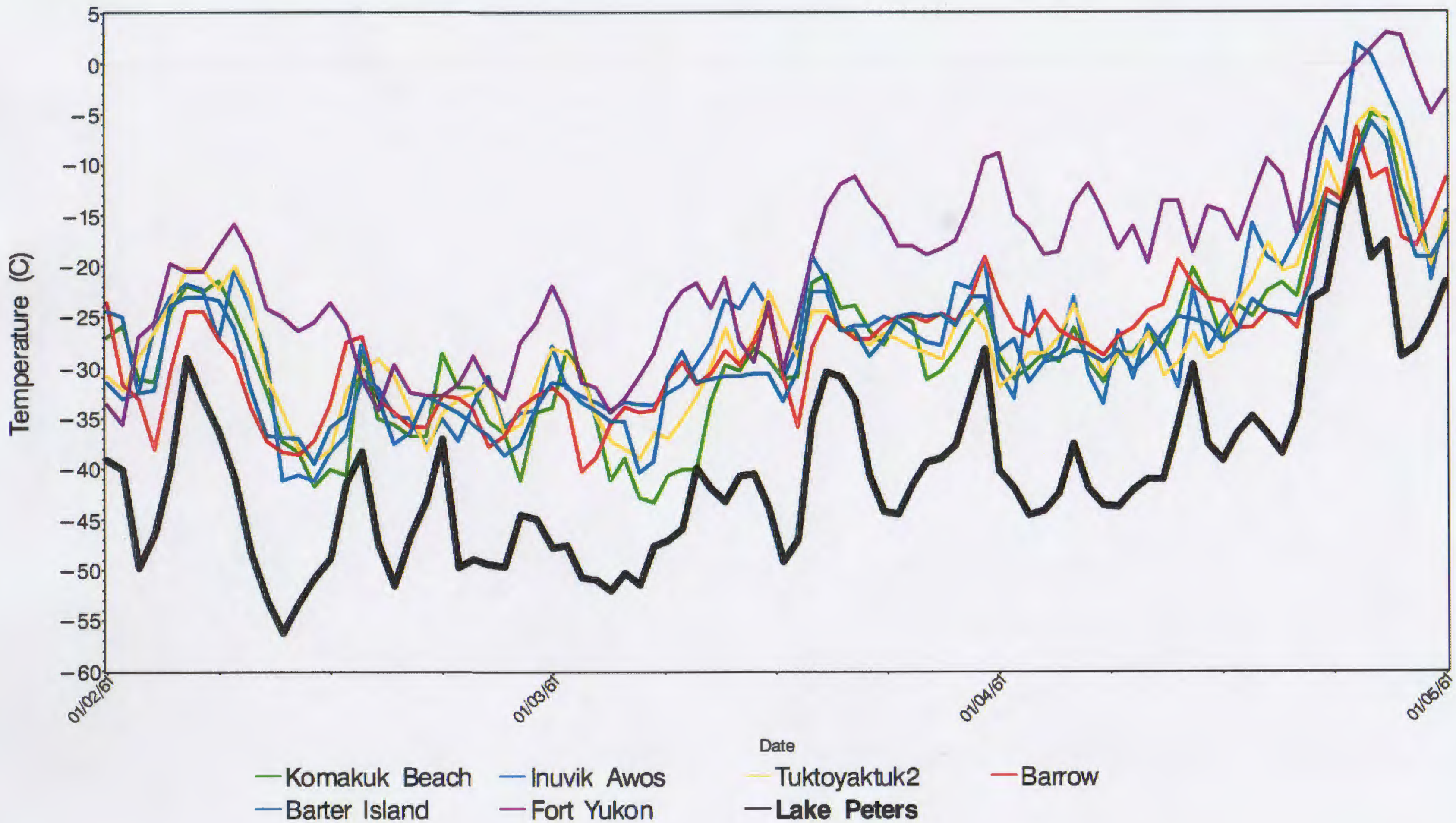
-50
-55
-60
02/10/60
02/11/60
02/12/60
02/01/61
02/02/61
Date
Komakuk Beach
Inuvik Awos
Tuktoyaktuk2
Barrow
Barter Island
Fort Yukon
Lake Peters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−60
01/02/61
01/03/61
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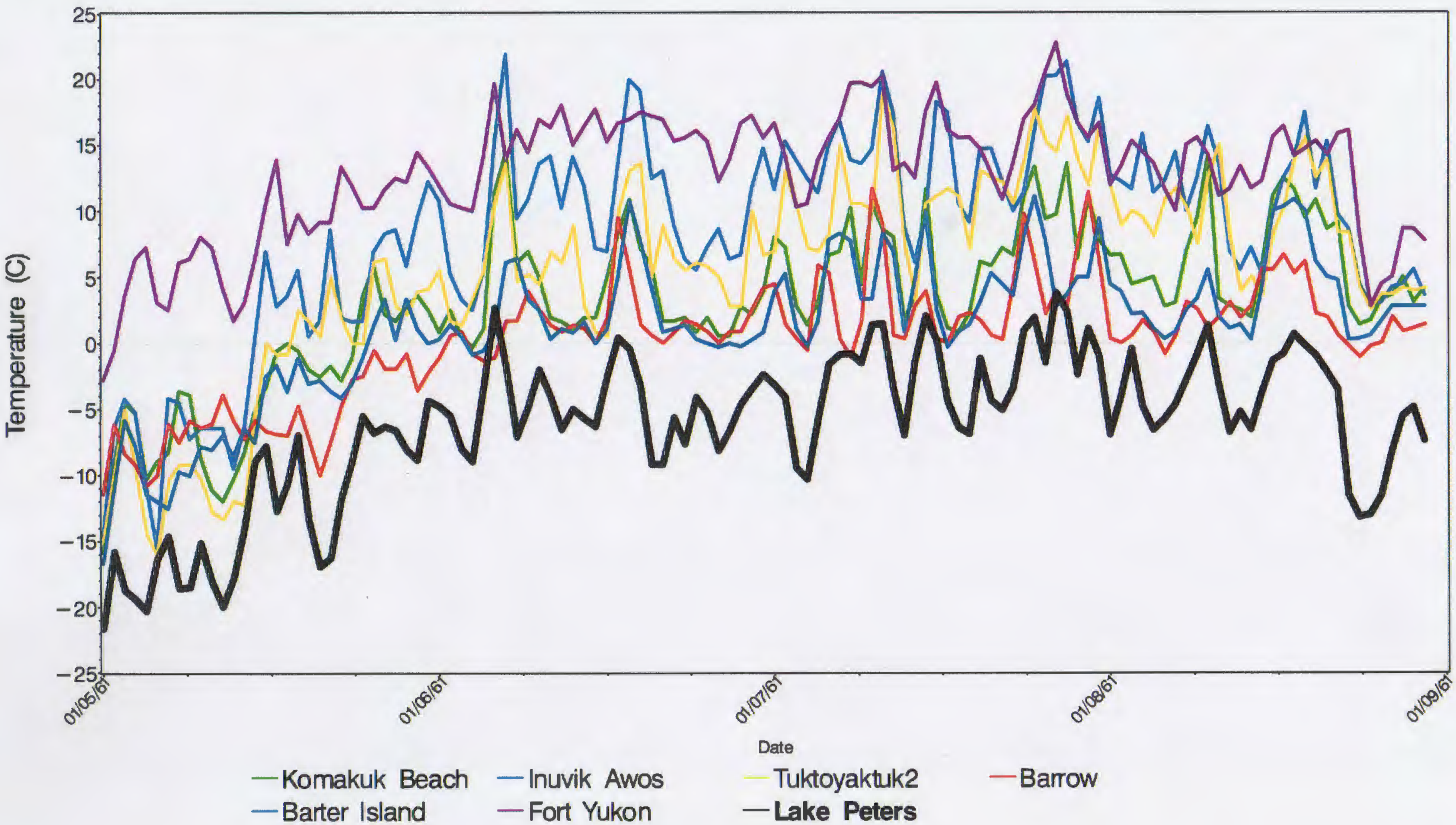
01/05/61
Date
Komakuk Beach
Inuvik Awos
Tuktoyaktuk2
Barrow
Barter Island
Fort Yukon
Lake Peters


Temperature (C)
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01/05/61
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01/07/61
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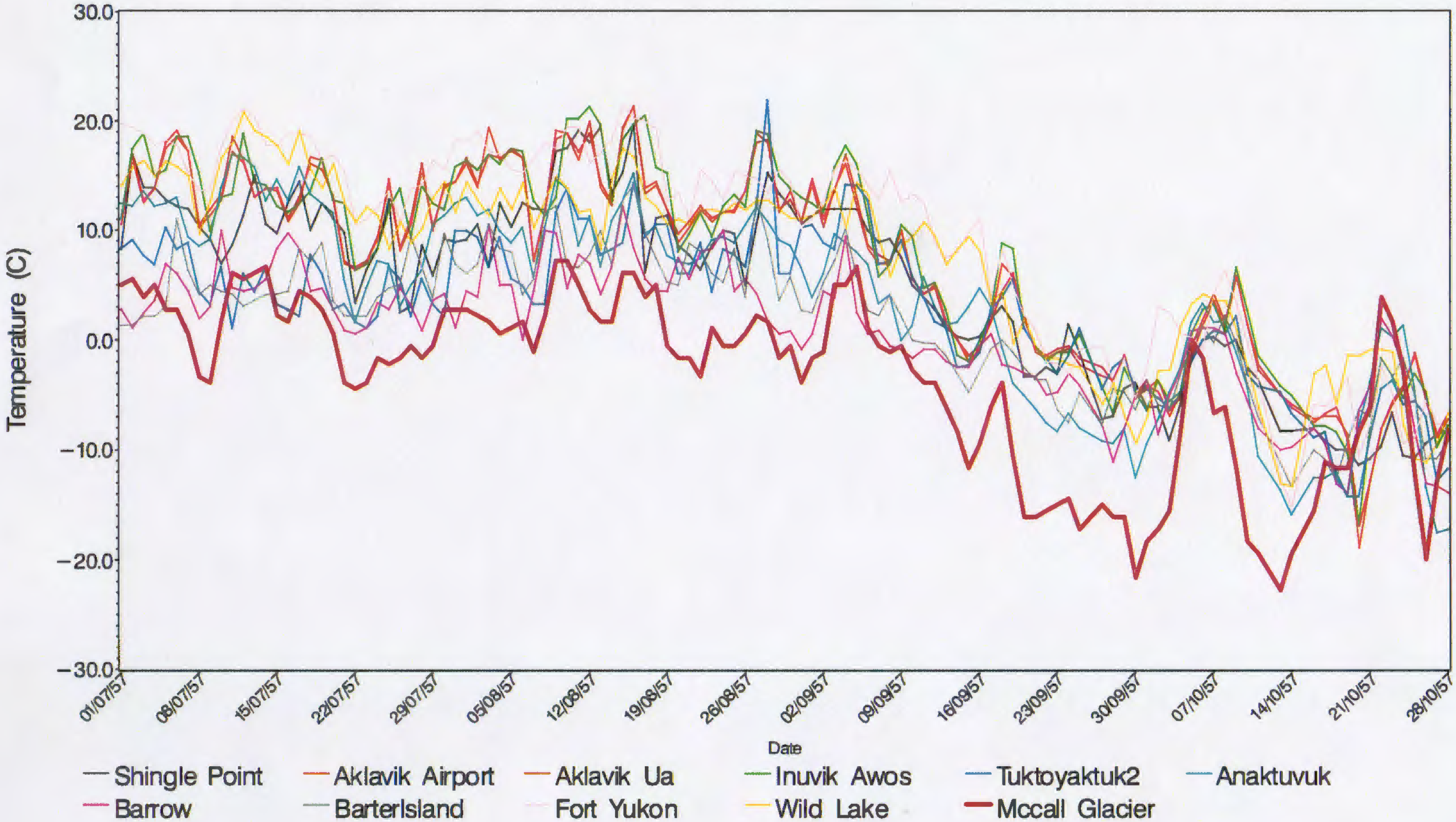
01/09/61
Date
Komakuk Beach
Inuvik Awos
Tuktoyaktuk2
Barrow
Barter Island
Fort Yukon
Lake Peters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20.0
10.0
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−20.0
−30.0
Temperature (C)
01/07/57
08/07/57
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29/07/57
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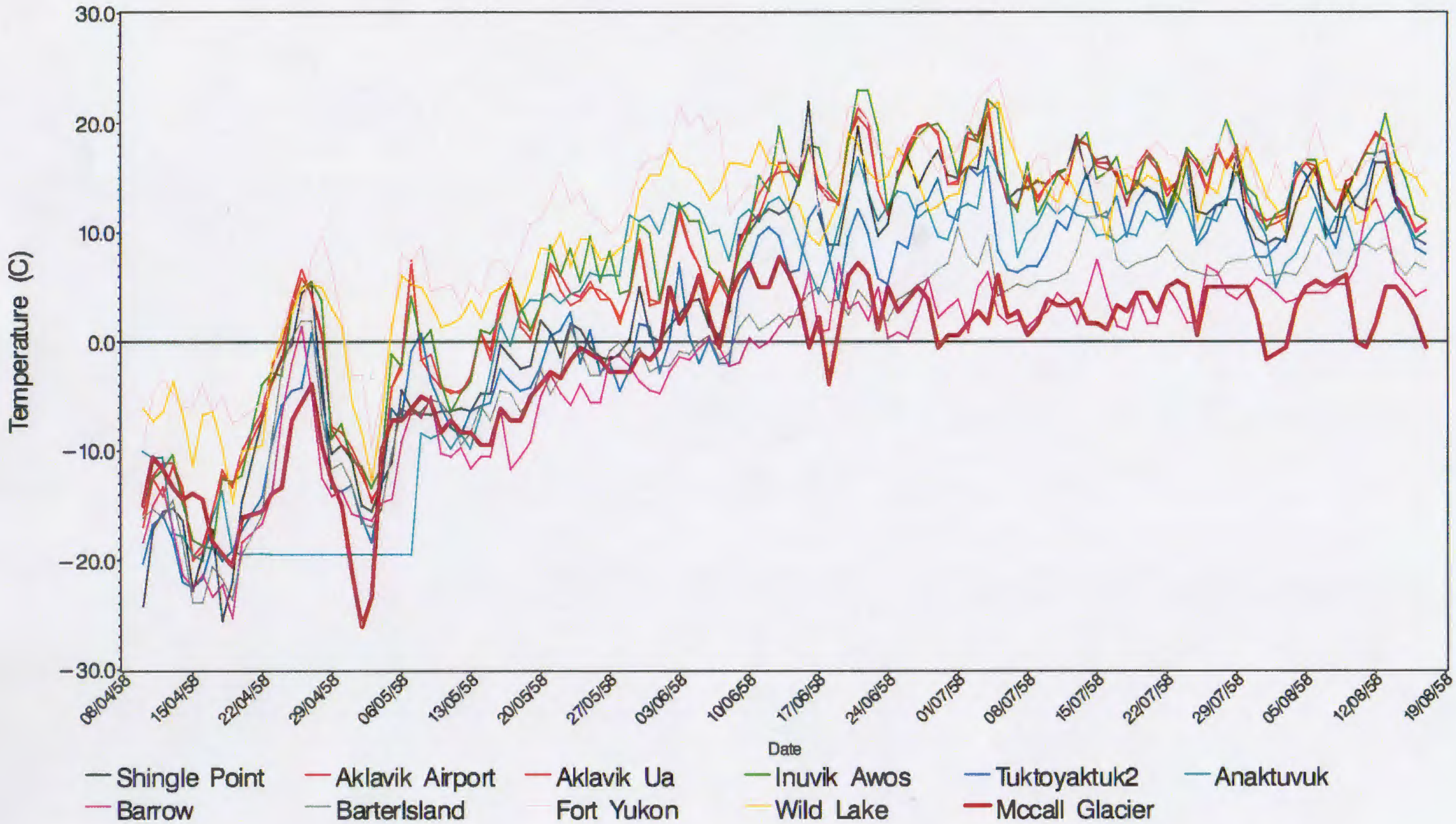
23/09/57
30/09/57
07/10/57
14/10/57
21/10/57
28/10/57
Date
Shingle Point
Aklavik Airport
Aklavik Ua
Inuvik Awos
Tuktoyaktuk2
Anaktuvuk
Barrow
BarterIsland
Fort Yukon
Wild Lake
Mccall Glacier


Temperature (C)
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−10.0
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08/04/58
15/04/58
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08/07/58
15/07/58
22/07/58
29/07/58
05/08/58
12/08/58
19/08/58
Date
Shingle Point
Aklavik Airport
Aklavik Ua
Inuvik Awos
Tuktoyaktuk2
Anaktuvuk
Barrow
BarterIsland
Fort Yukon
Wild Lake
Mccall Glacier

Appendix 2: Correlation and Cluster Analyses

Correlation analysis

Correlation analyses proceeded using the Pearson product moment of correlation, typically identified as "R". It is essentially a measure of standardized covariance, emphasizing the sequential co-variability of two time series. The formula for co-variance is given as:

$$Cov(x,y) = \frac{1}{n-1}\sum_{i=1}^{n}\left[(x_i - \bar{x})(y_i - \bar{y})\right]$$

To minimize the potential impact on this measure that variables with large ranges would exert, each time series variable is standardized against its respective standard deviation, which renders the correlation metric is insensitive to data magnitudes. An important implication is that it also therefore does not give any indication about the range between two data series – it responds only to pattern. The formula is:

$$r_{xy} = \frac{Cov(x,y)}{s_x s_y} = \frac{\frac{1}{n-1}\sum_{i=1}^{n}\left[(x_i - \bar{x})(y_i - \bar{y})\right]}{\left[\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{1/2}\left[\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2\right]^{1/2}}$$

Cluster analysis

A cluster analysis groups observations or variables according to some measure of similarity. The similarity measure D is often the Euclidian distance in K-space, where K represents the number of, in this case, data points in the time series. D may be expressed for data points from time t=0 to time t=K using:

$$D = \sqrt{(x_{t0} - y_{t0})^2 + (x_{t1} - y_{t1})^2 + \cdots + (x_{tK} - y_{tK})^2}$$

Euclidian distance is used for this study. For a hierarchical cluster technique, as utilized for this study, the smallest distance is identified and the two locations are grouped into a single cluster. The cluster-grouping process continues until all members are part of one large cluster. Cluster analysis is sensitive to differences in magnitude, a point that must be considered when interpreting results. Where units of measurement differ, this point must be addressed by, for example, standardizing time series to mean=0 and standard deviation=1 before they are processed. However differences in temperature due to station location is an important piece of information about a location, in addition to the pattern formed by the time series trace, which should be factored in to improve the delineation of zones of similarity. However, problems can crop up when temperature magnitudes are similar for reasons of station elevation. For example, a mountain station could have a very similar temperature magnitude to a coastal station. This would lead a cluster analysis to inappropriately group them. One way around this problem is to correct for temperature differences due to elevation. This is a standard climatological practice; the resulting value is "corrected" or adjusted to sea level using the dry adiabatic lapse rate. This temperature value is termed potential temperature and typically takes the symbol (θ). For this study cluster analyses were performed on potential temperature.

Appendix 3:

Data CD included