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On the Storms Passing over Southern Baffin Island during Autumn 2005

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ABSTRACT. Although strong storms affect all regions of the Arctic, little research has focused on the details of their structure and evolution—particularly of the storms passing over southern Baffin Island. Such storms form in a variety of locations and often occlude before passing over the region. To study these storms, a field project was conducted at Iqaluit, Nunavut, in the eastern Canadian Arctic in the autumn of 2005. We launched rawinsondes into six storm systems and made detailed measurements that included ice crystal structure and snow accumulation. The storms had quite different histories: some produced strong winds; some produced snow, while others produced rain and freezing precipitation; and three led to record-breaking temperatures. The types of precipitation particles varied greatly, but aggregates and rimed particles dominated. When comparing the six storms, we found numerous similarities between the surface and the vertical atmospheric conditions, but there were also distinct differences.

Key words: eastern Canadian Arctic, autumn storms, synoptic conditions, precipitation, rawinsonde profiles

RÉSUMÉ. Même si de mauvaises tempêtes s'abattent sur toutes les régions de l'Arctique, peu de recherches ont été effectuées pour connaître les détails de leur structure et de leur évolution, plus particulièrement en ce qui a trait aux tempêtes qui passent dans la région sud de l'île de Baffin. Ces tempêtes se forment dans divers endroits et souvent, elles se ferment avant de passer dans la région. Pour étudier ces tempêtes, des travaux ont été effectués sur le terrain même à Iqaluit, au Nunavut, dans l'est de l'Arctique canadien à l'automne 2005. Nous avons lancé des appareils de radiosondage-radiovent dans six tempêtes et avons pris des mesures détaillées portant notamment sur la structure des cristaux de glace et l'accumulation de neige. La formation des tempêtes était très différente : certaines produisaient des vents violents, d'autres produisaient de la neige, d'autres encore produisaient de la pluie et des précipitations givrantes, et trois tempêtes ont donné lieu à des températures record. Le type de particules de précipitation variait beaucoup, bien que les agrégats et les particules givrées dominaient. En comparant les six tempêtes, nous avons constaté qu'il existait de nombreuses similitudes entre les conditions à la surface et les conditions atmosphériques verticales, mais qu'il y avait aussi de nettes différences.

Mots clés : est de l'Arctique canadien, tempêtes automnales, conditions synoptiques, précipitations, profils de radiosondage-radiovent

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INTRODUCTION

Strong storms frequently affect the eastern Canadian Arctic. Storms that occur in the autumn over this region are typically characterized by heavy snowfall, strong winds, and resultant blizzard conditions. The surface weather conditions during these storms are often extreme and can have negative impacts on transportation and surface infrastructure. Inuit, particularly those involved in travel and hunting activities, are especially vulnerable. In addition, Inuit have reported an increase in both sudden and unanticipated changes in the weather, and there are limitations to their adaptive capacities (Nunavut Tunngavik Inc., 2001; Nichols et al., 2004; Ford et al., 2006a, b; Gearheard et al., 2006; Henshaw, 2006; Laidler, 2006; Laidler and Elee, 2006).

There is concern that the frequency and intensity of storms will change in the future. Zhang et al. (2004) reported that cyclone activity and intensity have increased in the Arctic in the past 50 years, and McCabe et al. (2001) speculated that there will be a northward shift of storm tracks with global warming. Future climate simulations suggest a tendency for more severe storms, as well as a northward shift of storms tracks (Yin, 2005).

Arctic clouds, precipitation, and storms have been the focus of previous atmospheric studies. Studies focusing on understanding the formation of snow crystals were first carried out in the western Canadian Arctic in 1977 and continued for several winters (Kikuchi and Kajikawa, 1979; Magono and Kikuchi, 1980). The Beaufort and Arctic Storms Experiment (BASE), conducted in the autumn of 1994, studied the structure and evolution of mesoscale weather systems occurring over the southern Beaufort Sea and the Mackenzie River delta (Hanesiak et al., 1997; Asuma et al., 1998). The Arctic Cloud Experiment and the Mixed-Phased Arctic Cloud Experiment

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were conducted to further the understanding of Arctic cloud processes (Curry et al., 2000; Yannuzzi et al., 2005). The Mackenzie GEWEX Study was concerned in part with the role of cloud systems in the water cycle (Stewart et al., 2004), and a study that focused on cyclones and their impact on sea ice was conducted in Fram Strait in 2002 (Brümmer et al., 2005).

None of these published studies used rawinsonde data with a higher temporal resolution than the twice-daily operational launches to examine the structure of storms affecting the eastern Canadian Arctic. Given the importance of these storms, as well as the possibility that their frequency and intensity may change in the future, a better understanding of them is critical. To begin to address this issue, we conducted a field project in the autumn of 2005. The results presented here focus on storms affecting southern Baffin Island, particularly Iqaluit.

DATA SOURCES AND METHODOLOGY

Iqaluit, Nunavut, was chosen for the field project conducted from 17 October to 28 November 2005 because of its importance as a transportation and community center. Iqaluit (63.75˚ N, 68.55˚ W) is located in a fjord–river valley combination at the head of Frobisher Bay on southern Baffin Island (Fig. 1). On a horizontal scale of a few tens of kilometers, Iqaluit is flanked by two ridges that reach 600 m above mean sea level (ASL), with a predominant southeast-to-northwest orientation. Observations were made at the operational weather station, located at the Iqaluit airport at 34 m ASL.

Observations were made during six storms. To document the internal structure of the storm systems, rawinsondes were launched from the operational weather station into the passing storm systems at intervals of two to four hours.

Special precipitation measurements were also made. High-resolution photographs of precipitation particles were taken during Storms 1, 2, and 3. Precipitation particles were collected on velvet-covered pads and immediately photographed using a 5.3 megapixel Nikon D1x digital SLR camera equipped with a macro lens. Total accumulation measurements were also made.

Additionally, we used surface observations, surface and upper-air analyses, and model re-analysis data in the analysis. Long-term hourly surface data and daily almanac data for Iqaluit from 1953 through 2005, as well as hourly surface and daily almanac data for other observing sites in the eastern Canadian Arctic (see Fig. 1), were obtained from Environment Canada (Environment Canada, 2006a, b). For Iqaluit, we obtained additional surface observations recorded every minute by the Automated Weather Observing System (AWOS), as well as surface analyses performed at three-hour intervals from the Hydrometeorological Prediction Center (HPC) (National Weather Service, 2005a). Upper-air analyses were obtained from

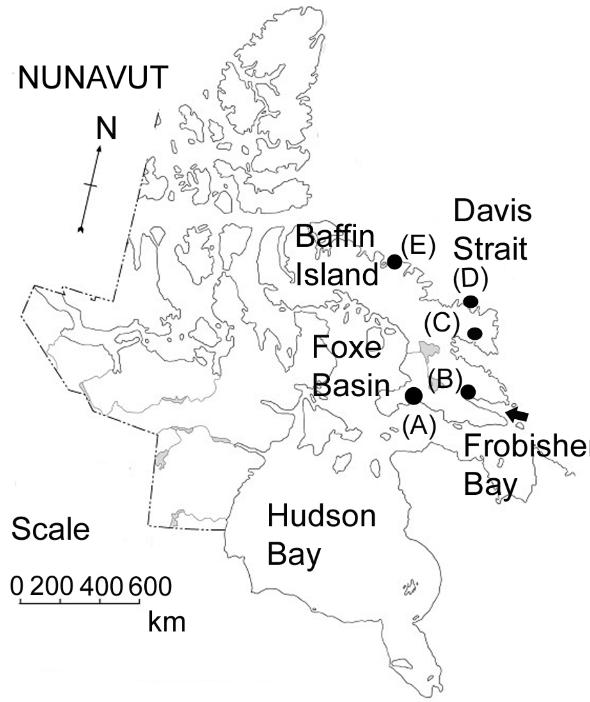

FIG. 1. Map of Nunavut (Natural Resources Canada, 2006), showing the locations referred to in the text: (A) Cape Dorset, (B) Iqaluit, (C) Pangnirtung, (D) Qikiqtarjuaq, and (E) Clyde River.

the National Oceanic and Atmospheric Administration (National Weather Service, 2005b). Finally, the North American Regional Reanalysis (NARR) was used to plot surface pressure and 1000–500 hPa thickness. The NARR is a high-resolution data set with a 32 km horizontal resolution and a 45 layer resolution covering the period from 1979 to the present at 3 h intervals (Mesinger et al., 2006).

OVERVIEW OF METEOROLOGICAL CONDITIONS DURING THE FIELD PROJECT

On average, October and November are the stormiest months of the year in the eastern Canadian Arctic (Maxwell, 1982). Heavy snowfall, strong winds, and below-freezing temperatures are common. However, unusually warm temperatures characterized October and November 2005, and in Iqaluit, temperatures averaged 4.7˚C warmer than normal. A higher occurrence of winds above 10 m s^{-1}, fewer hours of snow, and approximately the same number of hours with snow and winds above 10 m s^{-1} were observed during the field project in comparison to the 1980–2005 climatology.

The weather over Baffin Island during the field project was controlled mainly by the large-scale surface and upper-level pressure distribution (Fig. 2). In the first half of the field project, the combination of predominantly zonal flow in the upper levels and a persistent area of surface high pressure over northern Quebec prevented storms from tracking north towards Baffin Island: only weak

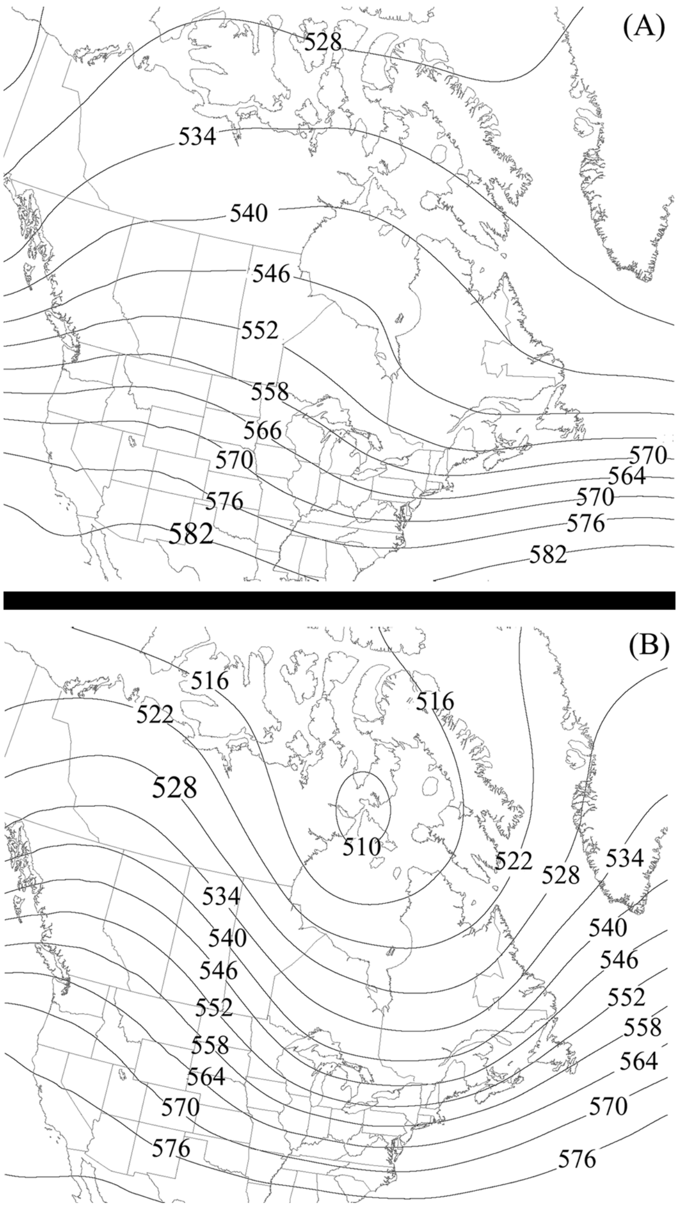

FIG. 2. Average 500 hPa (dam) height for (A) 16 October – 7 November 2005 and (B) 8 – 27 November 2005.

storm systems originating in the Northwest Territories affected the region. This pattern changed in the middle of November, when the polar vortex shifted from the High Arctic to the northern part of Hudson Bay. The resultant elongated trough and meridional flow allowed for more intense systems to track over Baffin Island from the south.

During the field project, detailed observations were made during six storms (Table 1). These storms produced snow, blowing snow, strong winds, fog, and rain, and were often associated with reduced visibility. Three maximum temperatures recorded in Iqaluit during the project set new records for those dates compared to the period 1953 – 2005. In addition, communities across Baffin Island were affected by these storms. To our knowledge, these storms did not have any major impact on residents, mainly because they occurred at night. Comparisons with similar wind and visibility conditions occurring during the day showed that with different timing, these storms could have led to disruptions of air traffic and other activities.

STORM 1

Synoptic Conditions

A low-pressure system that formed over the Northwest Territories and occluded before it reached Baffin Island affected Iqaluit on 30 October 2005, producing snow and blowing snow (Fig. 3). The occluded front passed over Iqaluit between 0600 and 0900 UTC on 30 October, and the low-pressure system then dissipated over Davis Strait. We define "dissipation" as the time when the region of low pressure was no longer represented by a closed contour. Because of its point of origin, the Storm 1 system had little moisture, and the amount of snow observed in Iqaluit was 2.5 cm, less than one-tenth of the mean monthly snowfall.

The evolution of surface parameters between 0000 UTC on 30 October and 0000 UTC on 31 October is shown in Figure 4. The passage of the occluded front was evident in the surface data. The surface temperature was steady near 0˚C at the beginning of the observation period and then decreased between 0600 and 1200 UTC, the period coinciding with the frontal passage. A sudden wind shift of 130˚ from south-southeasterly to west-northwesterly was observed between 0600 and 0700 UTC, as is common with systems originating over the Northwest Territories (Hudson et al., 2001). At Iqaluit, a minimum surface pressure of 982 hPa was observed at 1700 UTC on 30 October, approximately 12 h after the initial frontal passage. Surface winds were less than 15 m s^{-1} throughout the period. Visibility was reduced by blowing snow before the frontal passage and by fog and blowing snow for several hours after the frontal passage.

Other communities across Baffin Island were also affected by Storm 1. Freezing drizzle was observed at Qikiqtarjuaq, and snow was reported at Cape Dorset and Clyde River (Fig. 1). In addition, a record-high daily temperature of 0.8˚C (with respect to hourly surface data since 1953) was recorded on 30 October at Cape Dorset.

Vertical Atmospheric Conditions

Figure 5 shows a time-height cross section of wind speed and direction, temperature, and relative humidity between 0000 UTC on 30 October and 0000 UTC on 31 October. Weak winds aloft with speeds less than 30 m s^{-1} and weak directional shear of 100˚ to 130˚ were observed between the surface and 500 hPa. The frontal passage was evidenced between 0600 and 0900 UTC by a well-defined wind shift from southeasterly to northwesterly. Following the frontal passage, backing winds were observed between the surface and 700 hPa, one indication of cold air advection.

TABLE 1. Overview of storms passing over Iqaluit during the 2005 field project. The asterisks indicate record temperatures for the date.

Storm	Date Formed	Date Observed	Date Dissipated	Frontal Structure[1]	Minimum Pressure (hPa)	Snow Accumulation (cm)	Maximum Surface Temperature (˚C)	Maximum Surface Wind ($m\ s^{-1}$)	Minimum Visibility (km)	Surface Weather Conditions[2]
1	Oct 26	Oct 30	Nov 1	O	982	2.0	-0.2	12.7	0.8	SN, BLSN, FG
2	Nov 12	Nov 14–15	Nov 16	O	995	10.5	0.1*	10.3	0.8	SN, BLSN, FG
3	Nov 15	Nov 17	Nov 19	O	964	2.5	-1.4	15.5	0.5	SN, BLSN
4	Nov 21	Nov 24	Nov 24	W	980	7.0	0.9*	13.9	0.8	SN, BLSN, FG
5	Nov 24	Nov 25	Nov 25	O	985	2.0	0.3	11.3	0.5	SN
6	Nov 23	Nov 26	Nov 27	O	969	3.0	4.7*	28.7	0.5	RA, SN, BLSN, FG

[1] O = occluded front; W = warm front.

[2] SN = snow, BLSN = blowing snow, FG = fog, and RA = rain.

Slight cooling was observed throughout the atmosphere between 0000 and 1200 UTC. Finally, the atmosphere was saturated between the surface and 600 hPa during the first 12 h of the period.

Precipitation

Storm 1 produced numerous types of ice crystals (Fig. 6). The evolution of crystal types is correlated with the temperature and moisture profiles detailed in Figure 5. From the moisture profile, it is evident that the relative humidity was greater than 80% throughout the lowest 4 km for much of the observing period. This allowed for the formation of numerous types of crystals (for a classification, see Magono and Lee, 1966). Between 0200 and 0800 UTC, needles, dendrites, and sector plates were observed, and in many instances the crystals were rimed. Significant variation in crystal type was not noted until 1500 UTC, after which bullet rosettes, radiating plates, column collections, and intricate dendrites were observed. Although rimed crystals were observed after 1500 UTC, they were not as heavily rimed as those observed earlier. Rime crystals indicate an abundance of supercooled water droplets.

STORMS 2 AND 3

Synoptic Conditions

Storms 2 and 3 tracked over southern Baffin Island between 14 and 18 November. Before reaching Baffin Island, Storm 3 affected Ontario, where wind gusts as strong as 28 $m\ s^{-1}$ were observed, as well as parts of the United States, where 35 tornadoes were reported (Environment Canada, 2005).

Storm 2 affected Iqaluit on 14–15 November, and Storm 3, on 17–18 November. Both disturbances formed over the Midwest of the United States, tracked northeastward along the eastern shore of Hudson Bay, and occluded before reaching Baffin Island (Fig. 3). The occluded front associated with Storm 2 passed over Iqaluit between 0000 and 0300 UTC on 15 November, and the low-pressure center then dissipated over Davis Strait. The occluded front associated with Storm 3 passed over Iqaluit nearly three days later, between 2100 UTC on 17 November and 0000 UTC on 18 November. Shortly afterwards, the low-pressure center dissipated over Foxe Basin. Totals of 10.5 cm of snow (Storm 2) and 2.5 cm of snow (Storm 3) were observed at Iqaluit.

Figure 7 shows the evolution of surface parameters between 1200 UTC on 14 November and 1200 UTC on 18 November. A minimum surface pressure of 995 hPa, associated with Storm 2, was observed at 2300 UTC on 14 November. Prior to the passage of the occluded front, the surface temperature reached 0.1˚C, a record-high daily temperature and 13.0˚C warmer than the average daily temperature. The frontal passage was evidenced at the surface by a well-defined wind shift, from southeasterly to northwesterly, and a decrease in surface temperature. Although snow was recorded during most of Storm 2, no blowing snow was observed, which is attributable in part to wind speeds less than 9 $m\ s^{-1}$ and temperatures near 0˚C. Fog was observed in the hours immediately following the frontal passage.

Wind speeds in excess of 15 $m\ s^{-1}$, blowing snow, and reduced visibility were observed during Storm 3. At Iqaluit, a minimum surface pressure of 964 hPa was recorded at 0900 UTC on 18 November. Surface temperatures were near 0˚C during the storm. That the frontal passage (as depicted by the HPC surface analyses) was not evident in the local surface data is possibly due to the terrain, as no clear wind shift or temperature change was observed at Iqaluit. Previous studies have identified other storms in which the frontal passages were not evident in the surface data (Magono and Kikuchi, 1980; Maxwell, 1982; Taylor et al., 1993).

Other communities across Baffin Island were affected by Storms 2 and 3. For example, on 14 November surface temperatures as warm as 2.0˚C were observed in Pangnirtung, and on 15 November, a daily record high temperature of -2.0˚C was observed at Qikiqtarjuaq (Fig. 1). On 17 November, freezing drizzle was observed in Qikiqtarjuaq and Clyde River, wind speeds greater than 18 $m\ s^{-1}$ and blowing snow were reported in Cape Dorset, and wind speeds greater than 12 $m\ s^{-1}$ were observed in Pangnirtung.

FIG. 3. The tracks of the six observed storms that affected Iqaluit. The stars indicate successive positions of the storm at 12-hour intervals (locations recorded at midnight and noon). The dates on which each storm formed, passed over Iqaluit, and dissipated are shown in Table 1.

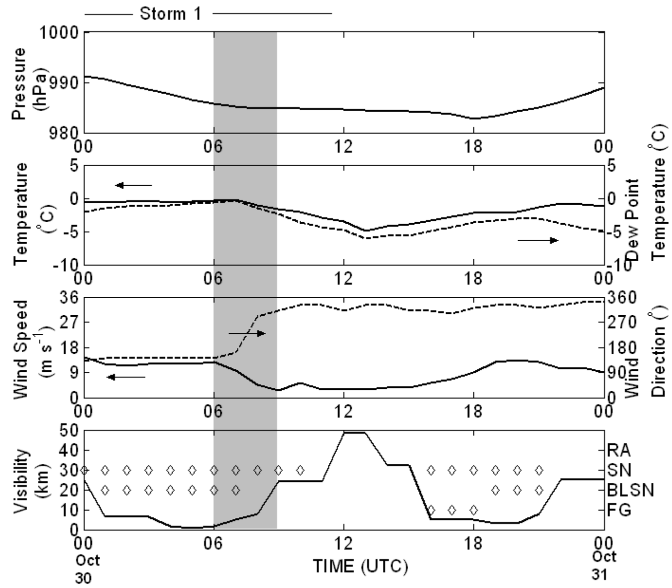

FIG. 4. Surface pressure (MSLP, hPa); temperature (˚C, solid line) and dew point temperature (˚C, dashed line); wind speed (m s^{-1}, solid line) and direction (˚, dashed line); and visibility (km) and weather conditions observed at Iqaluit between 0000 UTC on 30 October and 0000 UTC on 31 October 2005. RA = rain, SN = snow, BLSN = blowing snow, and FG = fog. Shading shows the time when the frontal passage of Storm 1 was observed. Arrows indicate which axis each line refers to.

Vertical Atmospheric Conditions

The time-height cross section for the period from 1200 UTC on 14 November to 1200 UTC on 18 November is shown in Figure 8. A strong vertical gradient in relative humidity was evident between 0000 UTC on 16 November and 0000 UTC on 17 November, during which time the relative humidity decreased from greater than 90% below 1 km to less than 70% above 1 km. A strong horizontal gradient in relative humidity, indicative of the occluded front, was also evident on 17 November, when relative humidity increased from below 70% at 0600 UTC to 80% at 1200 UTC. Precipitation formed aloft may often have been subjected to sublimation before reaching the surface. This may have contributed to low amounts of precipitation at the surface during Storm 3.

Several important features were noted in the wind field. During Storm 2, weak winds (< 10 m s^{-1}) were observed from the surface to 500 hPa. In contrast, stronger winds were associated with Storm 3 because of greater large-scale pressure gradients. Wind speeds of 10–15 m s^{-1} at the surface and 40 m s^{-1} aloft were observed on 17 November. In addition, a gradual weakening of the flow immediately above the terrain was observed between 1200 UTC on 17 November and 0000 UTC on 18 November.

Wind direction data show that winds veered with height, from southeasterly at the surface to south-southwesterly aloft, at 1800 UTC on 14 November and 0000 UTC on 15 November. Above the boundary layer, this phenomenon is associated with warm air advection. Surface winds were easterly and then southeasterly as Storm 3 approached. At 0000 UTC on 17 November, winds veered with height, from northeasterly at the surface to southwesterly at 500 hPa. In the lowest 5 km, larger directional wind shear was observed during Storm 2 (50–150˚) than during Storm 3 (10–60˚).

Precipitation

Storms 2 and 3 produced numerous types of ice crystals (Fig. 6). The evolution of crystal types is correlated with the temperature and moisture profile detailed in Figure 8.

At 1200 UTC on 14 November, conditions were conducive to the formation of dendrites, which develop in regions above water saturation at a temperature near -15˚C, and needles, which develop in regions above water saturation at a temperature near -5˚C. As the storm progressed, relative humidity decreased at upper levels, allowing for the formation of other crystal types, including plates, dendrites, and aggregates. In addition, many of the precipitation particles were rimed, indicating an abundance of supercooled water droplets.

The strong winds observed during much of Storm 3 made it difficult to differentiate between falling and blowing precipitation particles. At approximately 2100 UTC, the blowing snow subsided, and several crystal types, including aggregates, needles, and dendrites, were identified. Riming was again evident on many of the crystals.

STORMS 4–6

Synoptic Conditions

Storms 4 to 6, which tracked over southern Baffin Island between 0000 UTC on 24 November and 0000 UTC on 27 November, produced rain, snow, freezing precipitation, and strong winds at communities across Baffin Island (Fig. 3). During this period, the upper-level flow was

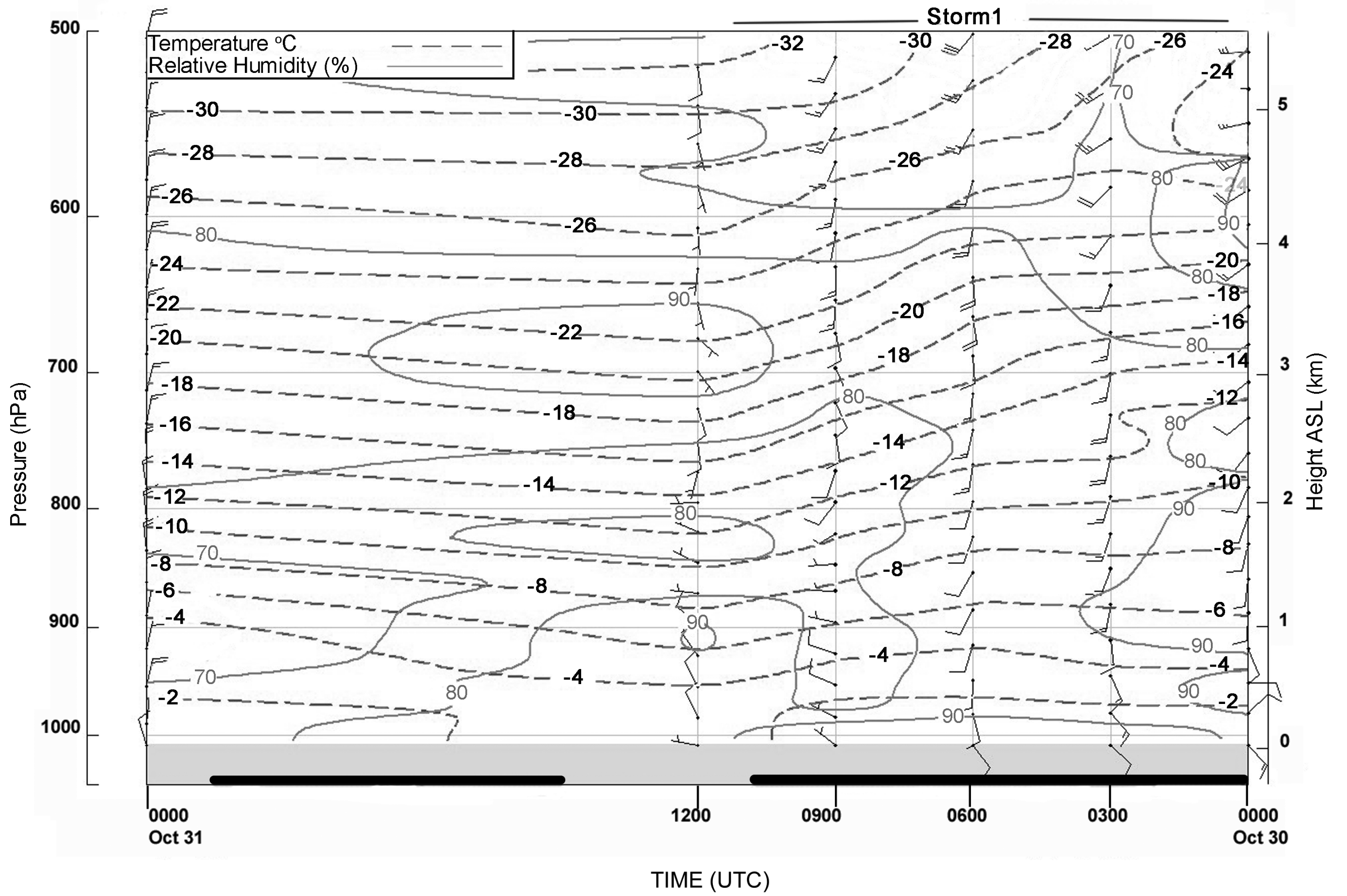

FIG. 5. Time-height cross-section displaying wind direction, wind speed, temperature, and relative humidity between 0000 UTC on 30 October and 0000 UTC on 31 October 2005. Time increases from right to left. The dark bar along the horizontal axis shows hours with observations of snow. Relative humidity contours are shown only when humidity is greater than 70%. Full wind barbs are equivalent to 10 m s^{-1} and half barbs are equivalent to 5 m s^{-1}.

dominated by an intense trough-ridge pattern, and a negatively tilted trough was evident in the upper-air analyses. A jet streak, defined as the region within the jet stream with the greatest winds, was situated on the eastern side of the trough (Fig. 9a). The surface low was situated below the left exit region of the jet streak (Fig. 9b). In this area, divergence aloft and enhanced vertical motion may have led to the intensification of Storm 6.

The surface analyses revealed key features of the three storms. Storm 4 formed over the Gulf of Mexico on 21 November and intensified over the next three days as it approached Baffin Island. A warm front passed over Iqaluit between 0000 UTC and 0300 UTC on 24 November and the low-pressure center passed to the northwest and then dissipated over Foxe Basin. Storm 5 formed off the coast of New Brunswick on 24 November and dissipated as it passed over Iqaluit between 2100 UTC on 24 November and 0000 UTC on 25 November. Storm 6 formed over the Canadian Prairies on 23 November, deepened as it moved through the base of the negatively tilted trough, and occluded before reaching Baffin Island. The occluded front passed over Iqaluit between 0900 UTC and 1200 UTC on 26 November, and the low-pressure system then dissipated over Foxe Basin.

The evolution of surface parameters at Iqaluit between 0000 UTC on 24 November and 0000 UTC on 27 November is shown in Figure 10. The frontal passage was evident in the Iqaluit surface data during Storms 5 and 6. During Storm 5, the surface temperature decreased, surface pressure increased, and a wind shift was observed following the passage of the occluded front. During Storm 6, a wind shift, from southeast to southwest, was observed with the frontal passage. At Iqaluit, the minimum pressure during the 72 h period, 969 hPa, was recorded during Storm 6 at 1100 UTC on 26 November, and the highest sustained surface wind speeds of 20 m s^{-1} and wind gusts in excess of 28 m s^{-1} were also recorded near this time.

Record-high daily temperatures were observed at Iqaluit during Storms 4 and 6. On 24 November, following the passage of the warm front associated with Storm 4, a record-high daily temperature of 0.9˚C was observed between 0900 and 1000 UTC. A record-high daily temperature for 26 November, 4.7˚C, was observed between 0800 and 0900 UTC just prior to the frontal passage associated with Storm 6.

Surface weather conditions varied between Storms 4 and 6. A total of 7.0 cm of snow was observed during Storm 4, as well as blowing snow and fog. Only 2.0 cm of

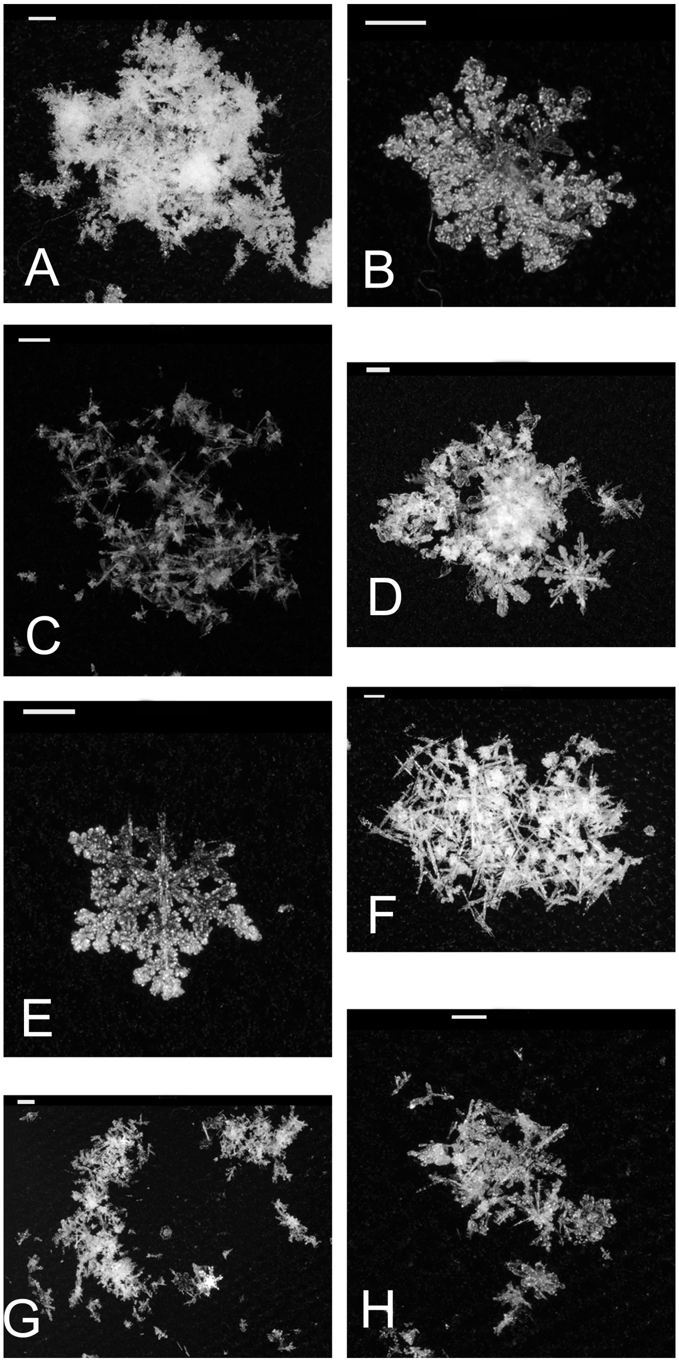

FIG. 6. Examples of ice crystals observed during Storm 1 (A, B, and C), Storm 2 (D, E, and F) and Storm 3 (G and H). All scale bars represent 1 mm in length.

snow was observed during Storm 5. Finally, a total of 3.0 cm of snow was observed during Storm 6, as well as rain, blowing snow, and fog.

Storms 4 to 6 also affected other communities across Baffin Island. Storms 4 and 5 produced snow at Cape Dorset for much of the 48 h period between 24 November and 25 November. A record-high daily temperature of -3.4˚C was recorded at Clyde River on 25 November. Storm 6 had the widest impacts. In Pangnirtung, a record-high daily temperature of 7.1˚C and wind speeds in excess of 19 m s^{-1} were observed on 26 November. Strong winds,

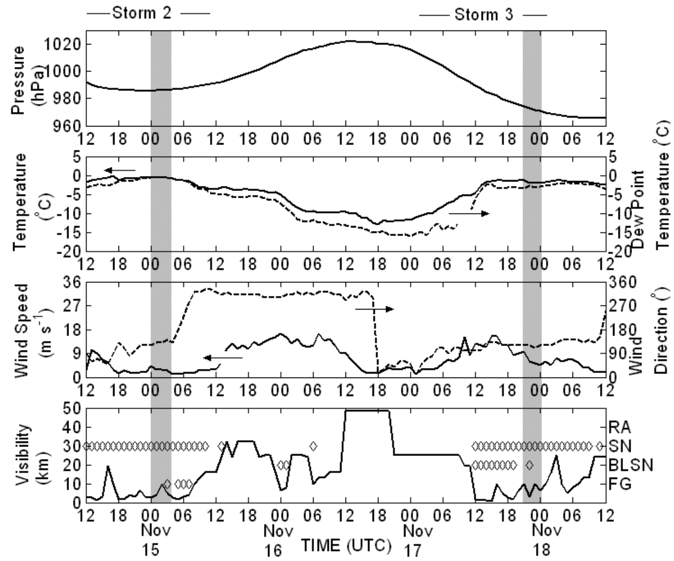

FIG. 7. As in Figure 4 but for the period between 1200 UTC, 14 November and 1200 UTC, 18 November 2005.

18 m s^{-1}, were also observed at Cape Dorset. Finally, rain and freezing rain were observed at Qikiqtarjuaq and Clyde River.

Vertical Atmospheric Conditions

Figure 11 shows a time-height cross section between 0000 UTC on 24 November and 0000 UTC on 27 November. Before 1200 UTC on 24 November, the relatively warm surface temperatures (> 0˚C) were due to the passage of a warm front associated with Storm 4. Significant warming was noted between 0000 and 1200 UTC on 26 November, and the 0˚C isotherm extended 1 km into the atmosphere.

In addition, several features were noted in the wind field that would not have been evident without the enhanced rawinsondes. First, the strongest mid-level winds were observed between 0000 and 1200 UTC on 26 November. Second, intense and potentially hazardous crosswinds were observed during the same time period.

DISCUSSION

Overview

Six storms were observed between 17 October and 28 November 2005 (Table 1). The storms had varied origins, produced strong winds, and were associated with widespread precipitation, including snow, rain, freezing rain, and freezing drizzle. The storms led to potentially adverse weather conditions at many communities across Baffin Island. However, mainly because of the timing of events, no documented major impacts were reported. Precipitation amounts varied between storms. Unusually warm temperatures and record-high daily temperatures were

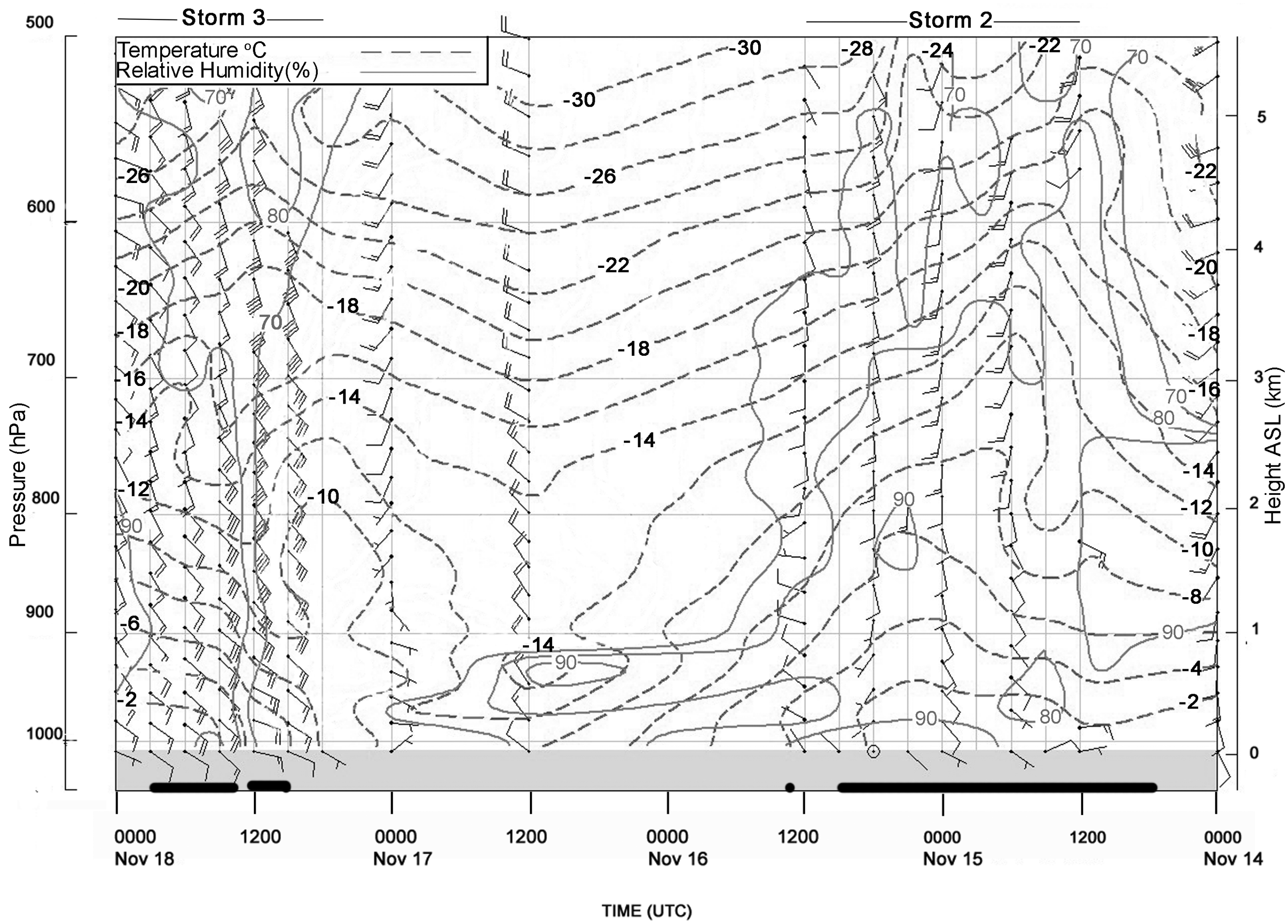

FIG. 8. As in Figure 5 but for the period between 1200 UTC, 14 November and 1200 UTC, 18 November 2005.

also observed at Iqaluit and other observing stations across Baffin Island.

It is evident that the storms originated in diverse locations (Fig. 3). Storms developed over the Northwest Territories, the central United States, the Gulf of Mexico, eastern Canada, and the Canadian Prairies. Five of the six storms occluded before reaching Baffin Island, and the central pressure of Storms 2, 4, and 6 increased soon after tracking over Iqaluit (Fig.12).

The locations of cyclolysis varied (Fig. 3). Three storms dissipated over Foxe Basin, two dissipated over Davis Strait, and one dissipated over southern Baffin Island (see Fig.1). Extratropical cyclones that dissipate over the Canadian Archipelago have been noted in other studies as well, for example, Intihar and Stewart (2005).

Low-Level Winds

Low-level jets, defined by high wind speeds within the boundary layer (≤ 1 km) relative to the flow above (< 5 km), are a potential hazard to aviation. These jets, which sometimes occur at Iqaluit, are typically located near ridge-top level (600 m). They are usually produced by persistent ageostrophic forcing below ridge-top level and maintained by topography (Nawri and Stewart, 2006).

Two low-level jets were detected in the analysis of 18 rawinsonde profiles with appropriate wind data (Fig. 13). In each case, the jet was produced by persistent ageostrophic forcing (defined as cross-isobaric flow), through large-scale, along-channel pressure gradients, evidenced by 20–40° of directional shear in the lowest 1 km (Figs. 5 and 8). The stronger low-level jet, observed during Storm 3, was located at 800 m just above ridge-top level, had a maximum wind speed of 26 m s^{-1}, and was associated with southeasterly flow ahead of the frontal passage. The weaker jet, observed during Storm 1, was associated with northwesterly flow following the frontal passage.

There were several reasons for the relative lack of jets in the remaining rawinsonde profiles. For the most part, it was evident that the low-level winds were southeasterly and weaker than the upper-level winds (Figs. 5, 8, and 11). Under such conditions, low-level jets did not form. This result is consistent with a low-level jet climatology completed by Nawri and Stewart (2006), which showed that, on average, wind speed increased with height when southeasterly winds were observed at the surface during the cold

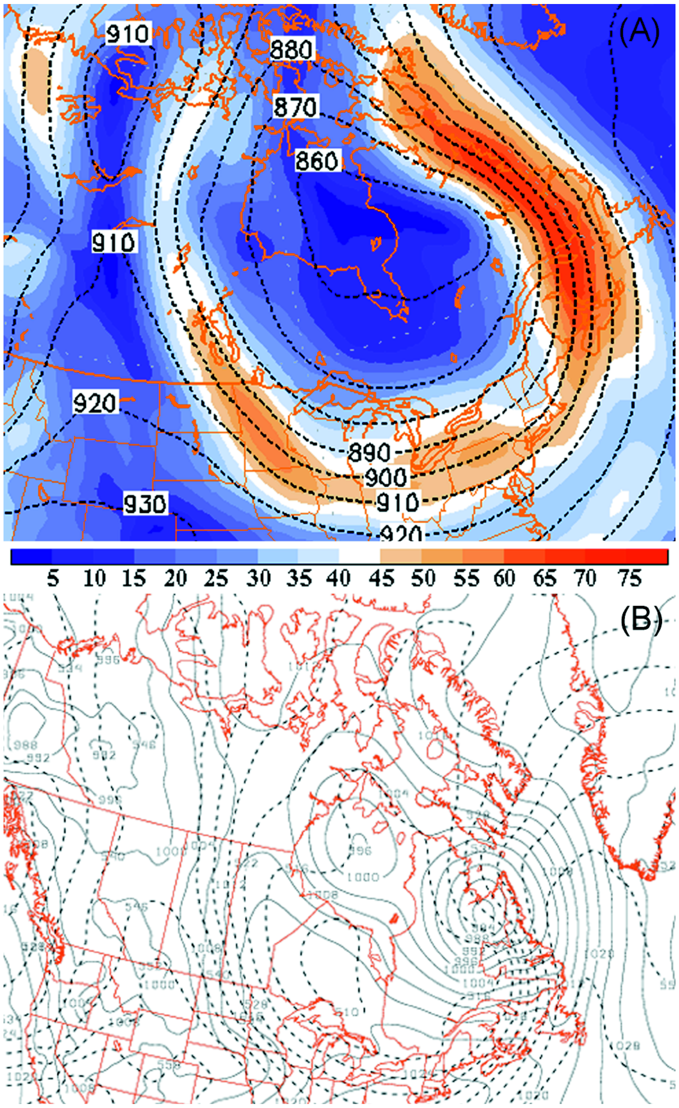

FIG. 9. (A) 300 hPa winds (shaded lines, m s^{-1}) and geopotential height (dashed lines, dam) (B) surface pressure (solid lines, hPa) and 1000–500 hPa thickness (dashed lines, dam) for 0000 UTC, 26 November 2005.

season. In addition, low-level jets do not form when the upper-level flow is too weak or too strong. Weak upper-level flow is indicative of weak large-scale pressure gradients and weak turbulent momentum transfer to lower levels. Strong upper-level flow, on the other hand, results in strong vertical momentum transfer and a breakdown of channeling as the flow adjusts to geostrophic balance, thus eliminating ageostrophic forcing due to large-scale pressure gradients. Such factors prevented the formation of low-level jets.

Surface Wind and Temperature

To compare key aspects of the six storms, the temperature and surface wind speed and direction recorded at Iqaluit for the 12 h period before and after each frontal passage, as indicated by the HPC surface analysis (National Weather Service, 2005a), are shown in Figure 14.

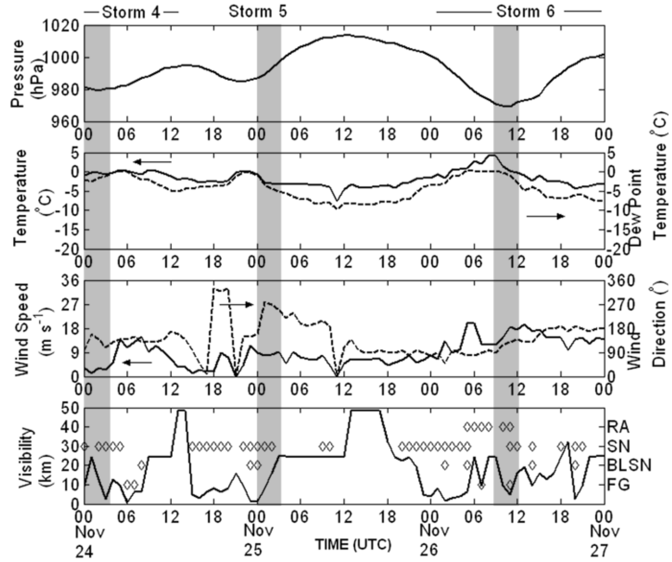

FIG. 10. As in Figure 4 but for the period between 0000 UTC, 24 November and 0000 UTC, 27 November 2005.

Frontal passages, evidenced by a well-defined wind shift or temperature change, were noted in every storm except Storms 3 and 4. For the four storms with clear frontal passages at the surface, either well-defined wind shifts or temperature changes were noted. The surface fronts were weak and difficult to identify in Storms 3 and 4. A wind shift and temperature change were not observed until 12 h after the frontal passage associated with Storm 3. Previous studies have identified other storms in which the frontal passages were not evident in the surface data (Magono and Kikuchi, 1980; Maxwell, 1982; Taylor et al., 1993).

Additional comparisons of the six storms can be made. Warm temperatures were associated with southeasterly winds, and the strongest winds were from southerly to southeasterly directions. The warmest surface temperatures and strongest winds were associated with Storm 6, although the lowest surface pressure at Iqaluit was observed during Storm 3 (Table 1). Strong winds often persisted for long durations. For example, winds stronger than 9 m s^{-1} were observed for 7 hours during Storm 3 and 34 h during Storm 6.

Three record-high daily temperatures occurred at Iqaluit. These were 0.1˚C on 14 November (Storm 2), 0.9˚C on 24 November (Storm 4), and 4.7˚C on 26 November (Storm 6). The records were observed in the early morning during Storms 4 and 6 and at midday during Storm 2. The record temperature observed during Storm 4 was recorded as the low-pressure center passed to the northwest, and the record temperatures observed during Storms 2 and 6 were recorded before the passage of the occluded front. Therefore, the three temperature records at Iqaluit were observed with overcast conditions and strong southeasterly flow.

Similar weather conditions have been observed with other record high temperatures recorded at Iqaluit during November. The daily almanac for Iqaluit from Environ-

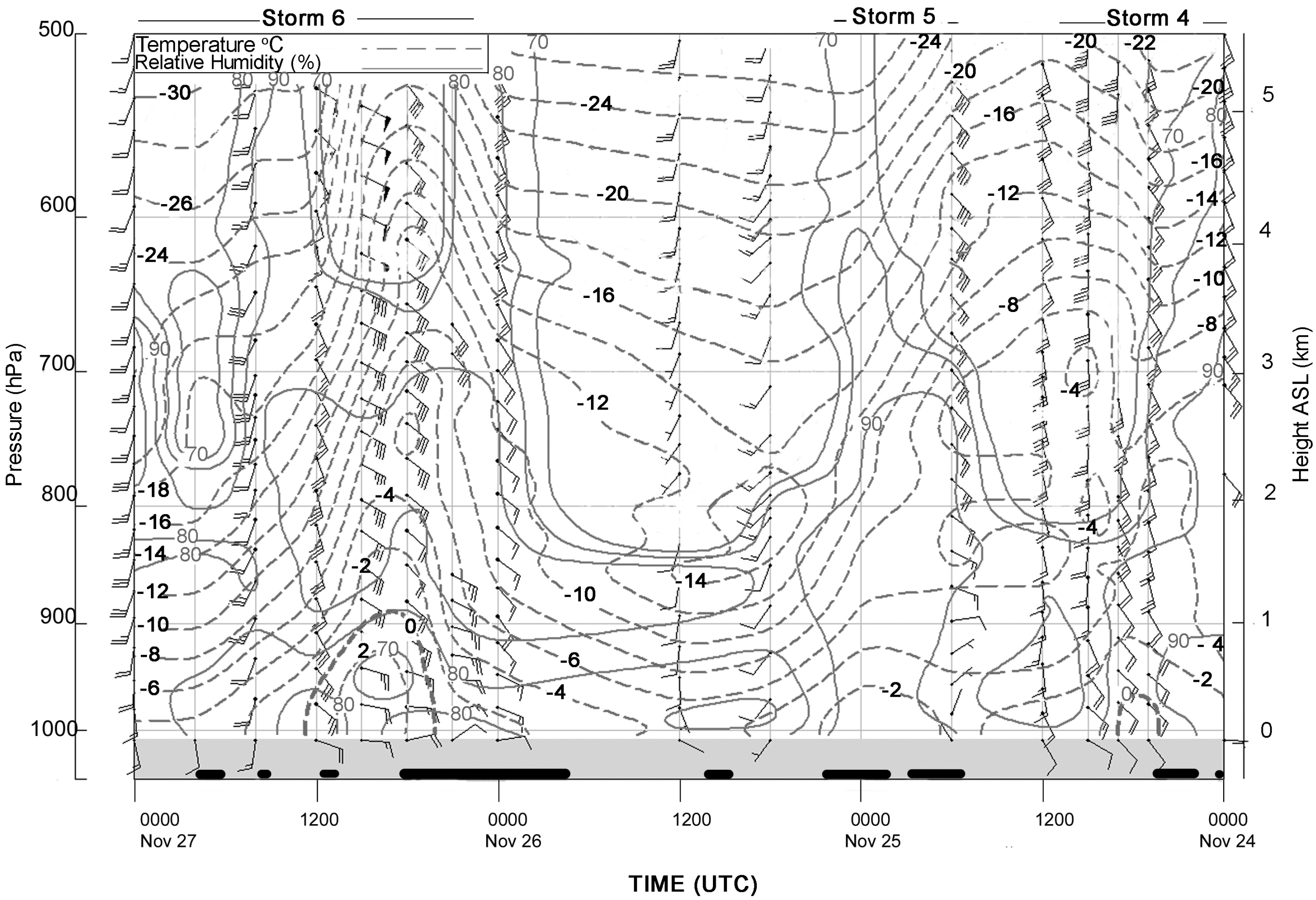

FIG. 11. As in Figure 5 but for the period 0000 UTC, 24 November and 0000 UTC, 27 November 2005.

ment Canada (Environment Canada, 2006b) lists record temperatures. Although hourly data are available for only 22 of the 30 days, record-high daily temperatures were recorded on 19 of those days before 1000 LST or after 1900 LST, and all 22 record highs occurred while skies were overcast.

Precipitation

The detailed nature of the solid precipitation produced within each storm varied dramatically. First, the precipitation consisted of individual crystals, aggregates, and accreted particles. Second, the types of crystals included columns, needles, plates, and dendrites. Third, accretion was common, although not continuous, and the degree of riming varied from light to extreme. Collectively, these findings revealed a complex environment within each storm and indicated the occasional presence of supercooled water within mixed-phase clouds.

Mixed-phase clouds, clouds containing both supercooled liquid and ice particles, are common in all seasons in the Arctic (Shupe et al., 2006). Further analysis of the vertical atmospheric conditions observed during the autumn field project revealed that cloud top temperatures ranged from -11˚C to -34˚C while accreted particles were observed. Supercooled liquid has been documented in clouds with cloud top temperatures as cold as -30˚C to -40˚C (Shupe et al., 2006; Verlinde et al., 2007). Therefore, the occurrence of accreted particles in the autumn of 2005 is quite consistent with results of other studies.

Weather Elements

Visibility was often reduced by fog and blowing snow (Table 1). During the six storms, a total of 11 h of fog and 27 h of blowing snow were observed. From the AWOS data, it was determined that during observations of fog and blowing snow the visibility ranged from 0.5 to 2.9 km. In addition, visibility was generally poorer during periods of blowing snow (1.0 km on average) than during periods of fog (2.1 km on average).

Several features were revealed in the analysis of fog. Although fog was observed most often with southeasterly winds, it was also observed with both northwesterly and easterly winds. Several factors, such as temperature differences between the air and the ground and open water, may have caused the fog to form. In the autumn of 2005, significant ice did not form within Frobisher Bay until

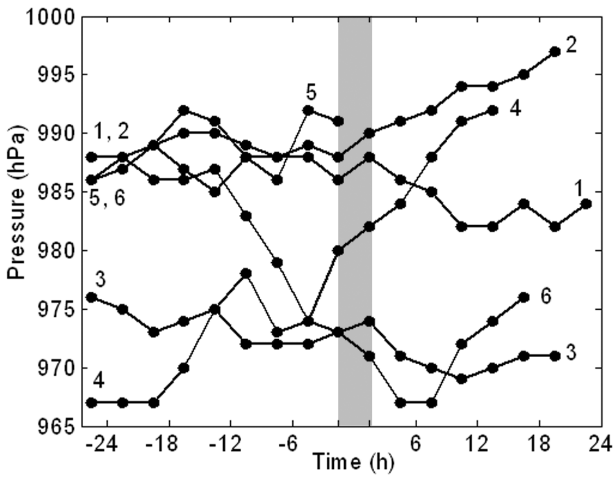

FIG. 12. The central pressure of each low-pressure system in the hours before and after the frontal passage associated with the specified storm. The shaded region represents the period during which the frontal passage was observed at Iqaluit.

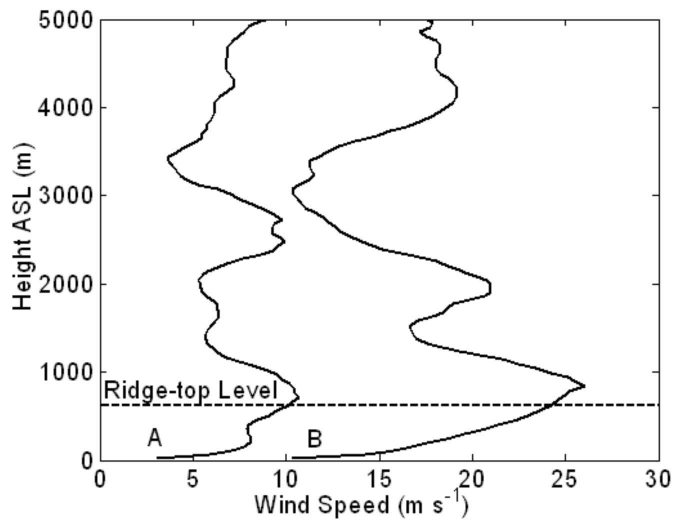

FIG. 13. Profiles of the low-level jets observed at (A) 1200 UTC, 30 October and (B) 1800 UTC, 17 November 2005. The ridge-top level is indicated. The winds are plotted at a 40–80 m vertical resolution.

November 14 (Canadian Ice Service, 2005), and the combination of open water and southeasterly flow may have led to the formation of advection fog. Previous studies have shown that advective processes are responsible for a majority of the observations of Arctic fog (Rae, 1951).

The occurrence of blowing snow was associated with different surface weather conditions. Blowing snow was observed with both northwesterly and southeasterly winds with speeds ranging from 13 to 38 m s^{-1} and with temperatures ranging from -5.2˚C to 0.7˚C. In comparison, winds greater than 9 m s^{-1} and temperatures colder than -2.5˚C were associated with blowing snow in Newfoundland (Stewart et al., 1994). Depending on the snow condition, the wind speed needed to initiate blowing snow ranged from 4 to 11 m s^{-1} over the Canadian Prairies (Li and Pomeroy, 1997). The threshold of 13 m s^{-1} observed during the six storms was therefore higher, possibly because when lower wind speeds were observed, there may have been no snow on the ground.

CONCLUDING REMARKS

Changes in wind speed and direction (as well as other variables) over complex terrain may occur within a few hours, so data collected every 12 hours will fail to detect many significant wind events (such as wind shifts, low-level jets, and wind gusts). The enhanced rawinsonde profiles used in this study allowed for a more detailed analysis of frontal structure, a more in-depth analysis of the temporal scale of low-level jets, and a better appreciation of precipitation processes. Data with higher temporal resolution may also help to determine the exact evolution and timing of significant wind events with respect to other variables, including temperature and precipitation.

For example, the storm during which the lowest surface pressure was recorded at Iqaluit was not associated with the strongest winds or the most snow accumulation. Although the minimum surface pressure at Iqaluit (965 hPa) occurred during Storm 3, the strongest winds at both the surface (28 m s^{-1}) and aloft (50 m s^{-1}) occurred during Storm 6, when a minimum surface pressure of 969 hPa was recorded at Iqaluit. In contrast, the greatest snow accumulation (10.5 cm) was observed with the weakest low-pressure system, Storm 2. The least snow accumulation (2.0 cm) was observed during Storm 1 and Storm 5, when minimum surface pressures of 982 hPa and 985 hPa, respectively, were observed at Iqaluit.

Above-normal temperatures were observed throughout much of the field project and more specifically during each storm. During the field project the average temperature at Iqaluit was 4.7˚C above normal. In addition, record high temperatures were recorded on three days: 0.1˚C on 14 November, 0.9˚C on 27 November, and 4.7˚C on 26 November. The first and third record-high daily temperatures were observed ahead of an occluded front, while the second record temperature was observed following a warm frontal passage as the low-pressure center passed to the northwest. In the third case, the layer with above-freezing temperatures reached approximately 1 km above the surface, high enough that above-freezing temperatures would have occurred over the nearby terrain as well. Thus the record temperatures were observed during storm passages and with overcast conditions, as opposed to during a sunny afternoon.

The storms often produced hazardous surface conditions. In addition to strong winds and precipitation, we observed low visibility due to fog or blowing snow (with and without precipitation). Blowing snow occurred more often than fog and was associated with the lowest visibilities. At times, blowing snow and fog acted to reduce the visibility to less than 2 km. Fog was most often associated with weak (< 12 m s^{-1}) southerly winds from the

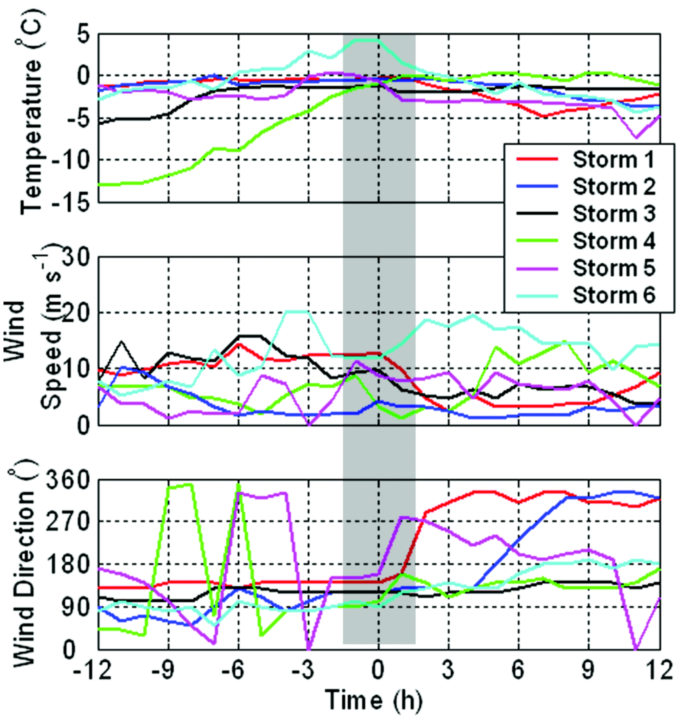

FIG. 14. Evolution of the specified surface parameters 12 h before and 12 h after the frontal passage associated with each storm. The shaded region represents the period during which the frontal passage was observed at Iqaluit.

ice-free Frobisher Bay. Sustained surface winds were on average twice as strong during blowing snow (12.3 m s^{-1}) as during fog (6.8 m s^{-1}).

There is concern that hazardous conditions associated with such storms will increase in the future. For example, rain was observed during the field project. Rain occurring with warm temperatures would act to melt the underlying snow and ice; this could lead to substantial runoff; and the ensuing liquid would later freeze and cover all surfaces with ice. Such conditions can have catastrophic consequences. There is also concern as to whether strong storms may become both more common and more intense over the region in the future (Yin, 2005). Stronger moisture and temperature advection would generally be associated with such storms, suggesting that winds, precipitation, and the likelihood of rain would all increase.

It is well known by forecasters and local residents that storms, particularly those occurring in the autumn, vary in many aspects, including origin, structure, wind, precipitation, and weather elements. However, this, to our knowledge, is the first study to quantify, document, and interpret some of the critical features of storms that affect southern Baffin Island. This analysis may serve both as a first step towards improved weather prediction in the region and as a basis for future observational and modeling studies.

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