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A climatology of adverse winter-type weather events

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Abstract. Using the European Centre for Medium-Range Weather Forecasts Re-Analysis gridded data, a global climatology of blowing snow, blizzard, and high-windchill events is conducted for the period 1979-1993. The results show that these phenomena occur primarily over flat, open surfaces with long seasonal or perennial snow covers such as the Greenland and Antarctic ice fields as well as the Arctic tundra. On a regional scale, emphasis is given to the Mackenzie River Basin (MRB) of Canada, where fewer events take place within the boreal forest as opposed to the Arctic tundra. Interannual and monthly variabilities in the number of events are also evident and are due primarily to 10-m wind speed anomalies at high latitudes for blowing snow and blizzard events, while high-windchill events are more sensitive to air temperatures near the surface. We also find that high-windchill episodes are the more frequent events, since they occur at 9.3% of all possible grid points and times on a yearly basis, while blowing snow at 6.5% and blizzards at 1.4% are less common events. Compositing of principal meteorological fields show that anticyclones and lee cyclones are prominent features associated with blowing snow events in some sections of the MRB.

1. Introduction

Cold-season processes often dominate the weather of high-latitude regions. Winter storms combine high windchills and blowing snow that produce blizzard conditions over wide expanses, crippling human activity and leading to substantial economic and social losses.

Despite the recurrence of adverse wintertime weather over widespread areas of the world and inconvenience to people, little is known on the actual frequency of these events. Observations are particularly difficult and scarce in the remote polar areas and over sea ice. Although climatological works for the Antarctic and Arctic are not uncommon [e.g., *Maxwell*, 1980; *Woo and Ohmura*, 1997; *King and Turner*, 1997], few provide climatic data on adverse conditions. Others have examined winter storms and associated processes without assessing their yearly distributions [e.g., *Stewart et al.*, 1995a]; hence our goal is to provide an analysis of the frequency of these events.

This study is motivated in part by the Mackenzie GEWEX Study (MAGS) [*Stewart et al.*, 1998], the Canadian component of the Global Energy and Water Cycle Experiment (GEWEX). The ultimate goal of MAGS is to evaluate the energy and moisture fluxes for the entire Mackenzie River Basin (MRB) of western Canada (see Figure 1). Since some of the processes influencing the wintertime water and energy budgets of the MRB are potentially associated with the transport of wind-driven snow and concurrent sublimation that occur during blizzards and other high-wind events [*Lawford*, 1993, 1994], a climatology of these events must be established. Given that the gridded data used in this study are global, an analysis is first presented for both hemispheres. We then proceed by examining the hemispheric trends and some causes of anomalous numbers in these events. Subsequently, we examine more closely the climatology as well as the synoptic-scale signatures of blowing snow events in the MRB, followed by a discussion of the results. The paper begins with some background information on the three significant wintertime processes of interest and a description of the methodology used to compile these events.

2. Background

2.1. Blowing Snow

A notable weather hazard associated with snowstorms is blowing and drifting snow. Intense blowing snow can decrease visibility to near zero and cause drifts several meters deep, making transportation extremely difficult [*Kind*, 1981]. Blowing and drifting snow occur when wind speeds exceed a certain threshold value and initiate the transport of snow that was formerly at the surface. Precipitating snow may also induce blowing snow, making the source of blown snow somewhat difficult to resolve in many instances. Two substantive processes are involved during blowing and drifting snow: saltation and suspension. Saltation is snow particles bouncing along the surface at heights of a few centimeters,

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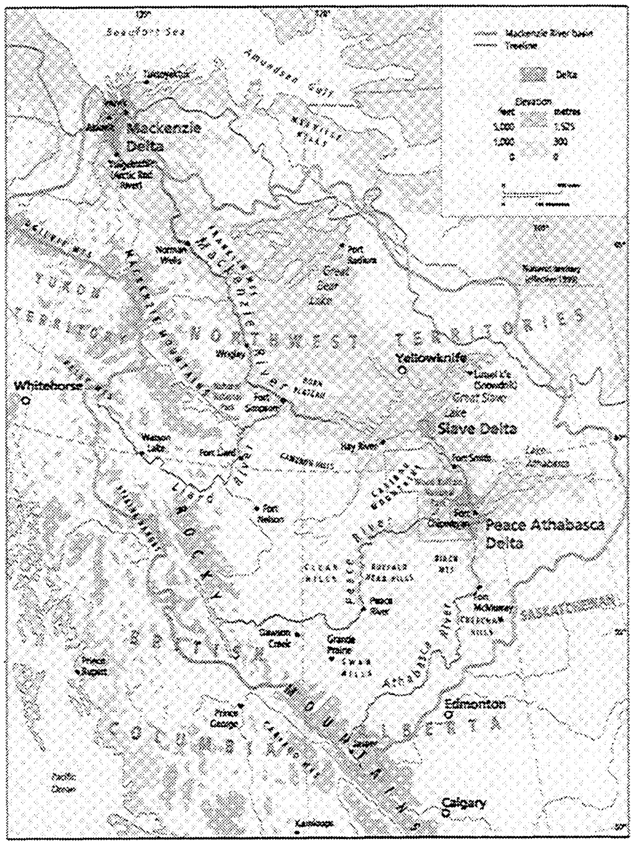

Figure 1. Geographical map of the Mackenzie River Basin. (Map produced by Eric Leinberger at the University of British Columbia for the Mackenzie Basin Impact Study [*Cohen*, 1997a, b].)

providing then a source for snow suspension [*Pomeroy et al.*, 1997]. Suspension occurs when snow particles are entrained by turbulent motions within the atmospheric boundary layer (ABL). In this mode, particles may rise to 100 m or more above the surface [*Pomeroy and Goodison*, 1997; *King and Turner*, 1997].

Although blowing snow usually refers to suspended snow that reduces visibility at eye level and drifting snow to snow transport below that height, we make no distinction between the two definitions in this work, and we will refer to the process as simply blowing snow. The 10-m wind speed threshold (U_t) for initiation of transport is usually in the vicinity of 5 to 10 m s^{-1} [*King and Turner*, 1997], depending on several environmental factors such as temperature and moisture conditions of the snowpack as well as the age of the snow [*Schmidt*, 1980]. Here we follow *Li and Pomeroy* [1997], who have found a dependence on the 2-m air temperature T_a (°C) for U_t (m s^{-1}) as

$$U_t = U_{t_0} + 0.0033(T_a + 27.27)^2 \qquad (1)$$

where the minimum value of the threshold 10-m wind speed, U_{t_0}, is equal to 6.98 m s^{-1} and is reached at about $T_a = -27$°C. This parabolic equation predicts higher resistance to transport at very cold temperatures and near the freezing point. Near 0°C, the snow tends to be wet, and the imbedded water leads to higher cohesion of the snowpack. On the other hand, at very cold temperatures, cohesion associated with strengthening elastic and frictional forces again reduce the capacity of the wind to displace snow from the surface. The intermediate range $-25°\text{C} < T_a < -10°\text{C}$ is defined by *Li and Pomeroy* [1997] as the cold cohesive regime in which wind transport of dry snow is generally most favorable.

2.2. Windchill

The combination of cold air and high winds leads to rapid loss of body heat, a process termed "windchill," which was first examined by *Siple and Passel* [1945] and subsequently by *Steadman* [1971], among others. An empirical relationship for windchill (WC, W m^{-2}) was derived to be [*Siple and Passel*, 1945]:

$$WC = (10.7 - 0.323T_a)(37.62 + 36.0U_{10}^{0.5} - 3.6U_{10}) \qquad (2)$$

with T_a in degrees Celsius and U_{10} the 10-m wind speed (m s^{-1}). As an example, for a wind of 11 m s^{-1} and $T_a = -20$°C, equation (2) yields $WC = 2.0$ kW m^{-2}, a common threshold at which windchill warnings are issued in Canada [*Atmospheric Environment Service*, 1988] and a value approximately at which exposed skin freezes in less than a minute.

2.3. Blizzards

"Blizzards" are winter storms that combine both high windchills and blowing snow, reducing visibilities markedly, as well as snowfall. "Ground blizzards" are winter storms with the same characteristics as blizzards but with no apparent snowfall. Although definitions may vary from region to region [e.g., *Bluestein*, 1993; *Wild*, 1995; *Branick*, 1997], a blizzard warning is usually issued in Canada when the following criteria are met for a period of at least 4 hours: (1) wind speeds > 11 m s^{-1} (= 40 km h^{-1}), (2) windchills > 1.6 kW m^{-2}, and (3) visibility < 1 km in snow and/or blowing snow [*Stewart et al.*, 1995a]. A temperature norm is at times utilized in place of windchill values, with $T_a < -12$°C, along with the other stipulated elements, usually marking the onset of a blizzard [*Phillips*, 1990]. Omitting the time component, blizzard conditions can occur at any time, and "blizzard hours" or "days with blizzards" are the most often recorded climatological quantities.

Even though blizzards are common phenomena in many regions of the world, such as Antarctica [*Alvarez and Lieske*, 1960], Eurasia [*Mikhel' et al.*, 1971] and North America [*Stewart et al.*, 1995a; *Branick*, 1997], few in-depth studies of blizzards exist in the literature. The climate studies of *Burns* [1973], *Maxwell* [1980], and *Lawson* [1987] provide some insight on typical conditions favoring the development of blizzards and the frequency of such events in Canada. Exceptional cases have also been described by, for instance, *Babin* [1975], *Graff and Strub* [1975], *Burrows et al.*, [1979], *Salmon and Smith* [1980], *Eagleman* [1990], *Kocin and Uccellini* [1990], and *Wild et al.* [1996].

3. Methodology

3.1. Definitions

Since observations of adverse wintertime processes are scarce and conducted in very harsh conditions, we have compiled a climatology of these events using gridded reanalysis data. Thus a 15-year (from 1979 to 1993 inclusive) climatology of significant cold-season "events" for the MRB and the globe is obtained from 6-hourly European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA) data on a 2.5° latitude × 2.5° longitude grid [*Gibson et al.*, 1997]. Subsequently, the results are converted to a polar stereographic projection, since the processes of interest occur mainly near the poles. The domains of the grids depicting the polar stereographic projections are composed of 50 × 50 points centered over the poles with a horizontal resolution of 250 km true at 60°N or S. The presence of snow is determined from the snow depth parameter of the ERA data that is based on station observations, but sea ice coverage is provided by the Canadian Meteorological Centre (CMC) at the same resolution as the former.

Definitions of the events are as follows. A blowing snow event is defined as any day when the surface was snow-covered land or sea ice (in concentration of 50% or more), the temperature was below 0°C, and the threshold velocity for transport was exceeded, as determined from equation (1), at any grid point. On the other hand, we consider a high-windchill event as any day when $WC > 2.0$ kW m^{-2} at any grid point. Finally, a blizzard event is interpreted as any day when blizzard conditions are met (see section 2.3) at any grid point, using the windchill and wind speed criteria, but necessarily omitting the time component given the temporal resolution of the ERA data. In addition, the visual range is not a parameter in the ERA data set and is therefore estimated from the following relationship [*Tabler*, 1979]:

$$VIS = AU_{10}^{-5} \tag{3}$$

where VIS is the approximate visibility (m) at eye level in blowing snow, A is a constant set to 10^8 m^6 s^{-5}, and U_{10} is in m s^{-1}. When $VIS = 1$ km, wind speeds are 10 m s^{-1}, corresponding essentially to the wind speed criterion for blizzard conditions. Although precipitation may also reduce the visual range, the wind speed threshold for blizzards ensures the incidence of blowing snow and ensuing deterioration in VIS below 1 km. A snow-covered surface (land or sea ice with concentration $> 50\%$) is a further requirement imposed for blizzard events. Note that unlike the case of a blowing snow event or a blizzard event, no temperature or wind speed threshold appears in the definition of a high-windchill event. Therefore a high-windchill event can occur if the temperature is cold enough, even for a small wind speed, as long as $WC > 2.0$ kW m^{-2}.

The ERA data are available four times daily (0000, 0600, 1200, and 1800 UTC). An event is considered to have occurred if the criteria for a specific event are satisfied at any one of the four times. However, for all grid points we limit the number of events to a maximum of one per day. This allows a comparison of our results with observations, since significant cold-season processes are often recorded only on a daily basis, i.e., a day with or without such an event.

3.2. Validation

To determine the validity of our analysis, tests were first conducted to verify the prediction of events with hourly surface observation (SA) reports at several Canadian meteorological stations during the month of March 1993. As an example, Figure 2 shows the near-surface fields of sea level pressure (SLP), temperature, and wind speed, as well as the areas experiencing some type of adverse wintertime weather at 1200 UTC on March 14, 1993. An intense low-pressure system, known as a "Superstorm" [e.g., *Huo et al.*, 1995], is battering the East Coast of North America. At the same time, an enhanced SLP gradient and strong winds are occurring over the Beaufort Sea in association with an anticyclone north of Alaska. Table 1 lists the surface observations recorded at six meteorological stations across Canada. The locations of the stations are shown in Figure 2d. In general, the surface parameters indicate reasonable agreement considering the resolution in our ERA data. Blowing snow is inferred from the ERA to occur along the Arctic coastline and in southern Québec and the Maritime provinces (Figure 2a) and is observed at four stations in the area, i.e., Inuvik, Montréal, Natashquan, and Stephenville (Table 1). Cold conditions prevail in the Nunavut Territory (NVT) and the Northwest Territories (NWT), with most areas surpassing the high-windchill threshold of 2.0 kW m^{-2} as observed in Baker Lake (Figure 2b). High windchill values and strong winds near the Gulf of St. Lawrence lead to blizzard conditions associated with the aforementioned Superstorm. Surface observations at the coastal stations of Natashquan and Stephenville in eastern Canada reveal the blizzard event that we infer from the ERA data (Figure 2c). Thus we are capturing accurately these synoptic-scale events from the reanalysis data set.

In addition to the above tests, we compared climatological observations of T_a and U_{10} in high-latitude regions to those of the ERA data and find generally good agreement (Table 2). As the data in Table 2 suggest, however, the ERA exhibits in some locations a significant negative 2-m air temperature bias. This bias occurs during winter and spring at high latitudes and is forced by the unrealistically high values of the surface albedo assigned to a snowcover [*Kållberg*, 1997; *Slingo*

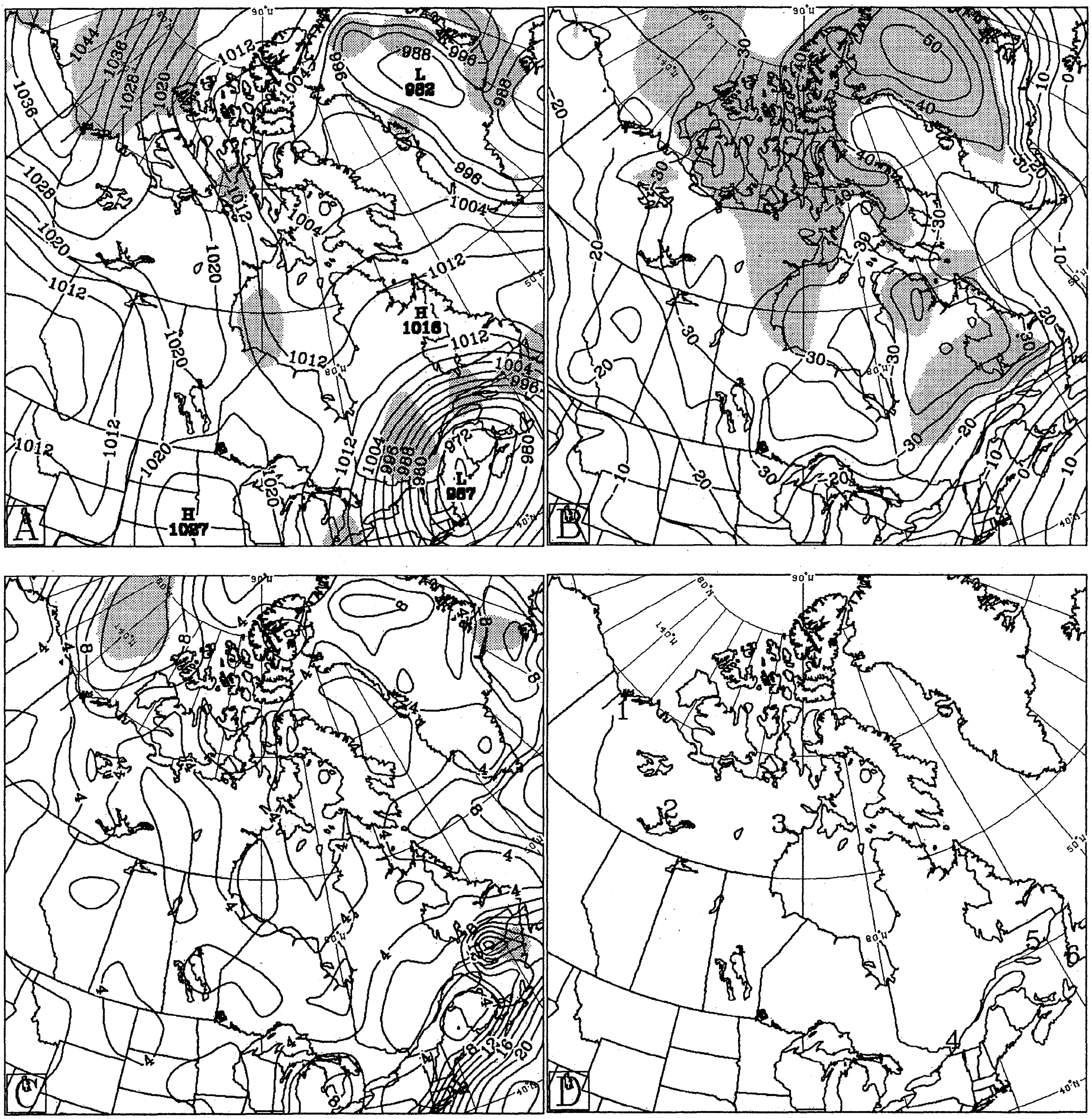

Figure 2. The contours of (a) the sea level pressure at 4 hPa intervals, (b) the 2-m air temperature at 5°C intervals, and (c) the 10-m wind speed at 2 m s^{-1} intervals, at 1200 UTC on March 14, 1993. Shaded areas indicate (a) regions experiencing a blowing snow event, (b) a high-windchill event, and (c) a blizzard event, as inferred from the ERA data. Refer to Table 1 for the locations numbered in Figure 2d.

et al., 1998]. Wind speed biases in both hemispheres are also evident in Table 2. The ERA underestimates wind speeds in the Antarctic coastal areas (e.g., Mirny) susceptible to frequent katabatic wind episodes [*King and Turner*, 1997]. Intense katabatic winds are mesoscale phenomena which may not be properly resolved by the ERA data at a resolution of 2.5°. In the Northern Hemisphere, both positive and negative wind speed biases (± 1 m s^{-1}) are observed. Negative wind speed biases would lead to an underestimate in the number of all three types of events of interest. On the other hand, negative temperature biases will reduce the frequency of blowing snow events when $T_a < -27°\mathrm{C}$ but increase the number of events in the range $-27°\mathrm{C} < T_a < 0°\mathrm{C}$, following our assumption for the threshold velocity for transport. For high-windchill and blizzard events, negative temperature biases will increase the frequencies of each. Note, however, that our sampling rate is limited to four times daily, whereas surface observations are often continuous in time. This may contribute to a lower number of days with a specific event as inferred from the ERA in comparison to actual observations.

For reasons of economy, we have used the ERA data at a resolution of 2.5°, which however, brings about limitations in detecting sub-synoptic-scale events. Both blowing snow and blizzard events are known to occur on

Table 1. Surface Observations of Sea Level Pressure (SLP), 2-m Air Temperature (T_a), 10-m Wind Speed (U_{10}), Windchill (WC), and Precipitation and/or Weather Type (PWT) Recorded at Selected Canadian Meteorological Stations at 1200 UTC on March 14, 1993

No.[a]	Station	SLP, hPa	T_a, °C	U_{10}, m s^{-1}	WC, kW m^{-2}	PWT[b]
1	Inuvik	1036.3	−21	6.7	1.86	S−, BS
2	Yellowknife	1020.3	−24	3.6	1.71	S−
3	Baker Lake	1017.8	−37	9.3	2.58	IC, IF
4	Montréal	981.3	−13	9.3	1.69	S−, BS
5	Natashquan	992.2	−10	12.3	1.66	S−, BS
6	Stephenville	992.6	−6	18.0	1.58	IP−, S−, BS

[a] The station number (No.) refers to its location in Figure 2d.

[b] The precipitation and weather types and their abbreviations are snow (S), blowing snow (BS), ice crystals (IC), ice fog (IF), and ice pellets (IP). A "−" indicates light precipitation.

the mesoscale as well as the synoptic scale [e.g., *Stewart et al.*, 1995b; *Szeto and Stewart*, 1997], and we recognize that these may not be entirely accounted for in the present work. In addition, alpine events are unlikely to be detected at this grid resolution. Although mesoscale and mountainous events would increase the overall frequencies of occurrences, particularly on a regional basis, we will show in the following section that our compiled frequency of adverse winter-type weather events compares favorably with the few observations found in the literature.

4. Results

4.1. Global Climatology

Figure 3 depicts the number of blowing snow events for both the Northern and Southern Hemispheres (NH and SH, respectively). Blowing snow events are most prominent on the windy and snow-covered ice fields of Antarctica and Greenland, as well as over sea ice. A high number of events also occurs on the Arctic tundra of Canada and Russia as well as the neighboring frozen seas and lakes. Forested areas increase surface friction and reduce wind speeds, limiting the number of occurrences there. This is evident in both North America and Asia, where the boreal forest endures fewer blowing snow events than the open plains south of the boreal forest (e.g., the Canadian prairies and steppes of Kazakhstan). Although climatological records of blowing snow are rare and definitions of events vary, we note a good correlation to that of *Phillips* [1990]. His blowing snow climatology for Canada portrays a similar local maximum in the prairies and a peak in the number of events in Hudson Bay, the NVT, and NWT, but with higher frequencies for the Arctic Islands and the prairies. The high number of events in Kazakhstan and along the Russian Arctic coastline also corresponds well to the regions of large volume transport reported by *Mikhel' et al.* [1971]. We remark, however, that alpine areas, prone to many blowing snow events [e.g., *Berg*, 1986; *Barry*, 1992], are not well represented here, except

Table 2. The Observed Mean Annual 2-m Air Temperature $\overline{T_a}$ and 10-m Wind Speed $\overline{U_{10}}$ at Selected High-Latitude Climatological Stations Compared to the Values Obtained From the ERA Data

Station	Latitude, Longitude	$\overline{T_a}$, °C		$\overline{U_{10}}$, m s^{-1}		Source
		Observed	ERA	Observed	ERA	
Northern Hemisphere						
Inuvik, Canada	68°N, 133°W	−4.5	−7.5	2.8	3.3	1
Novosibirsk, Russia	55°N, 83°E	−0.2	1.7	3.8	3.7	2
Vilyuysk, Russia	64°N, 122°E	−9.2	−10.3	2.2	3.1	2
Yellowknife, Canada	62°N, 114°W	−5.4	−6.4	4.3	3.1	1
Southern Hemisphere						
Byrd, Antarctica	80°S, 119°W	−27.9	−32.0	8.6	2.9	3
Halley, Antarctica	76°S, 26°W	−18.5	−12.7	4.8	5.5	3
Mirny, Antarctica	67°S, 93°E	−11.5	−15.0	11.5	8.6	3
South Pole, Antarctica	90°S	−49.3	−52.7	4.8	5.0	3

Sources: 1, *Environment Canada* [1993]; 2, *Lydolph* [1977]; 3, *Schwerdtfeger* [1970].

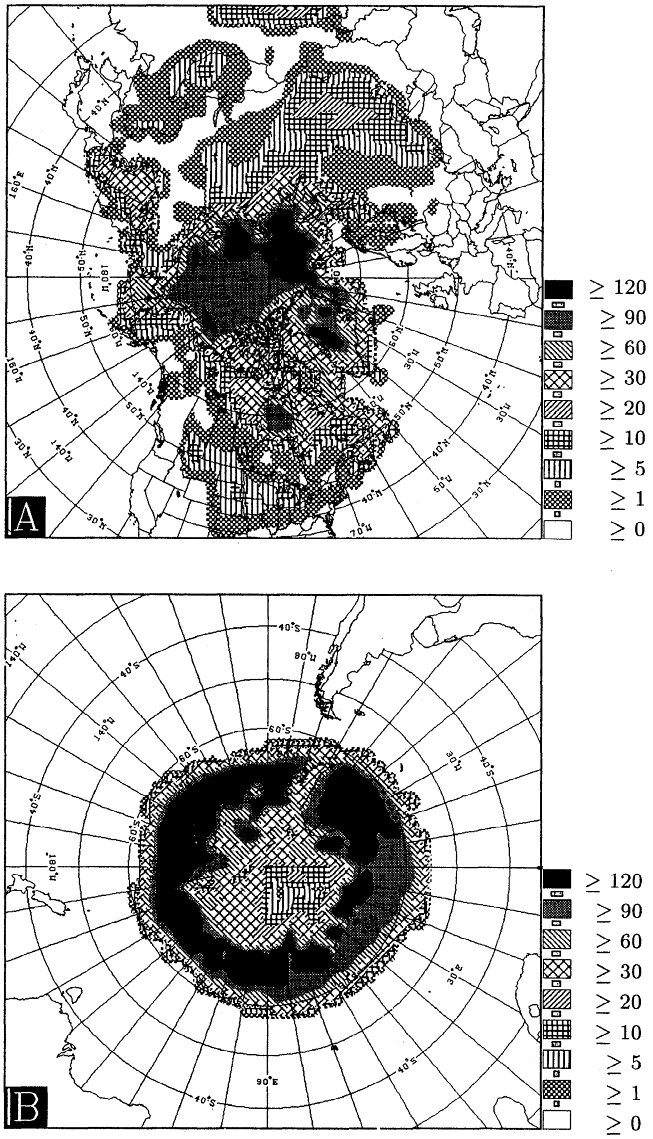

Figure 3. Mean annual number of blowing snow events (as defined in the text) for the period 1979-1993 in (a) the Northern Hemisphere and (b) the Southern Hemisphere.

perhaps the Tibetan Plateau, due to the resolution of the gridded data.

In the SH, a "ring" of maximum blowing snow events is associated with the stormy coastal regions of Antarctica and the circumpolar trough, with some areas experiencing blowing snow daily more than two thirds of the year (Figure 3b).

The annual number of days when WC surpasses 2.0 kW m^{-2} is presented in Figure 4. This shows that, on an annual basis, a greater number of blustery days occur in Antarctica as opposed to the ice-covered Arctic Ocean. However, the Asian and North American continents surrounding the Arctic Ocean promote a southward propagation of high-windchill events as far south as 40°N. In the SH these cold episodes rarely occur over open waters or even sea ice and do not extend much farther north than 70°S.

A climatology of blizzard events is also inferred from the ERA data, and this is plotted in Figure 5. Note the separate scales used for the NH and SH. We first observe a similarity between the zones of frequent blizzard events with those of blowing snow and high-windchill events shown in Figures 3 and 4. The ice-covered Arctic Ocean and polar seas, the ice fields of Greenland and Antarctica, as well as the barren lands of the Arctic tundra are favorable locations for the development of blizzards. Local maxima in North America are found in the Great Lakes regions (associated with lake-effect storms which are induced by the passage of cold air over the relatively warm open waters of the lakes), the Canadian prairies and U.S. Midwestern plains, although the frequencies of events found with the ERA data are somewhat less than observed there [*Lawson*, 1987; M.

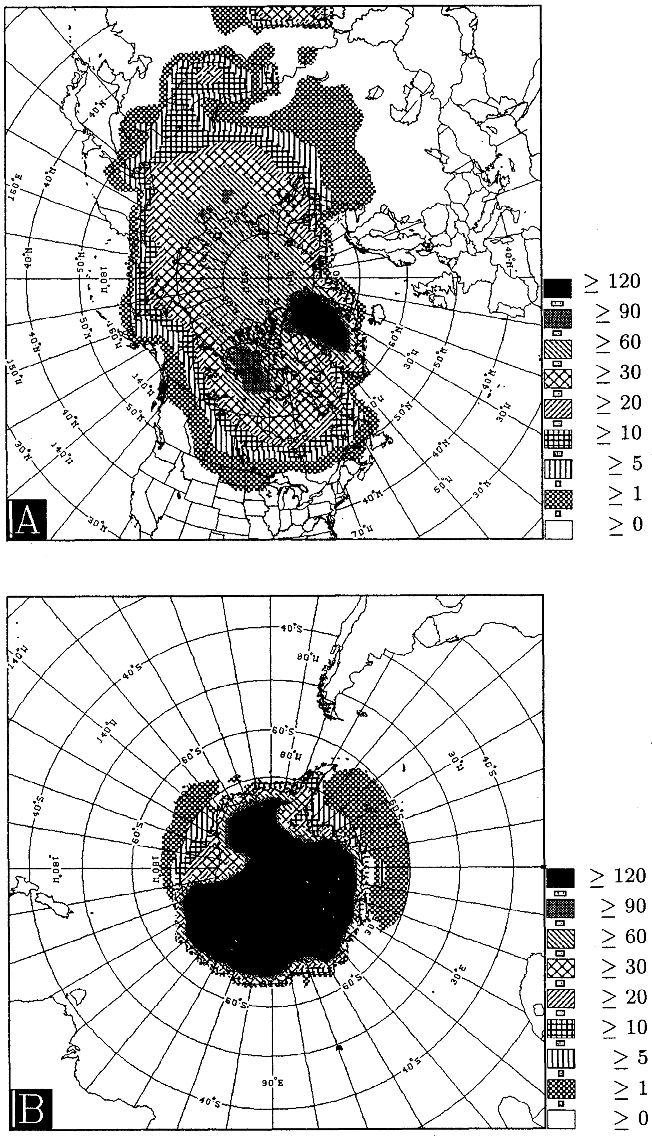

Figure 4. Mean annual number of high-windchill events (as defined in the text) for the period 1979-1993 in (a) the Northern Hemisphere and (b) the Southern Hemisphere.

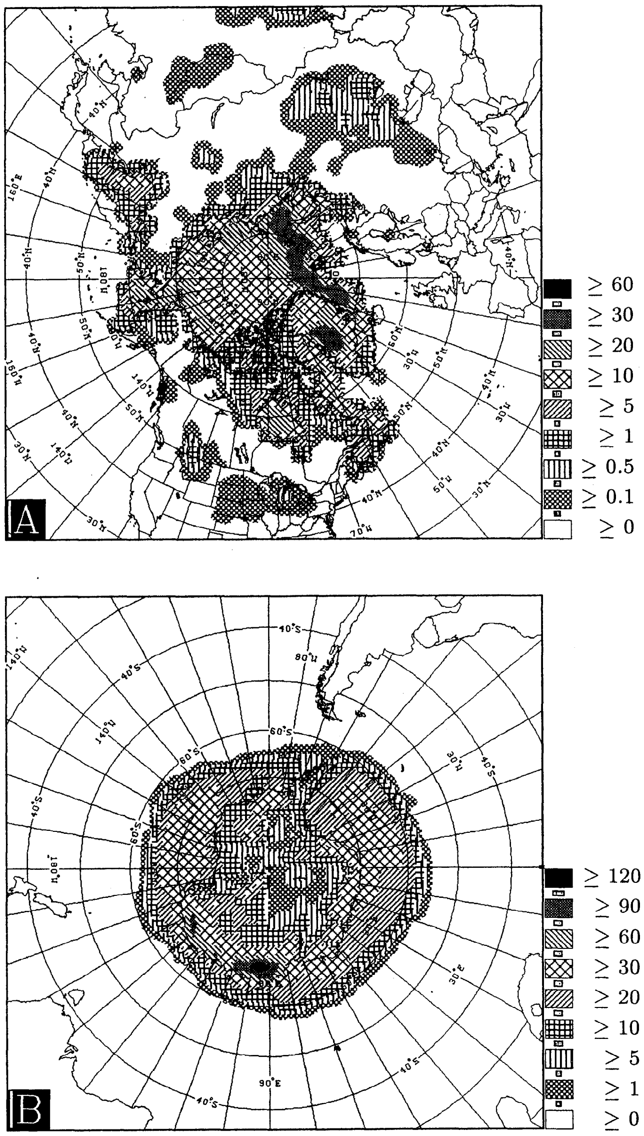

Figure 5. Mean annual number of blizzard events (as defined in the text) for the period 1979-1993 in (a) the Northern Hemisphere and (b) the Southern Hemisphere.

L. Branick, unpublished data, 1998]. Canada's East Coast is notorious for its frequent winter storms, many of which reach the status of blizzard. However, few blizzards are experienced where boreal forest prevails, again due to a significant reduction in high wind speed events there. In the SH, most events occur along the stormy coastal environment of eastern Antarctica, with some regions experiencing blizzards no less than 120 days annually.

4.2. Trends and Anomalies

Over the course of the 15 years investigated in this paper, monthly and annual variabilities in the number of adverse winter-type weather phenomena are evident from the time series of blowing snow, high-windchill, and blizzard events displayed in Figure 6. The time se-

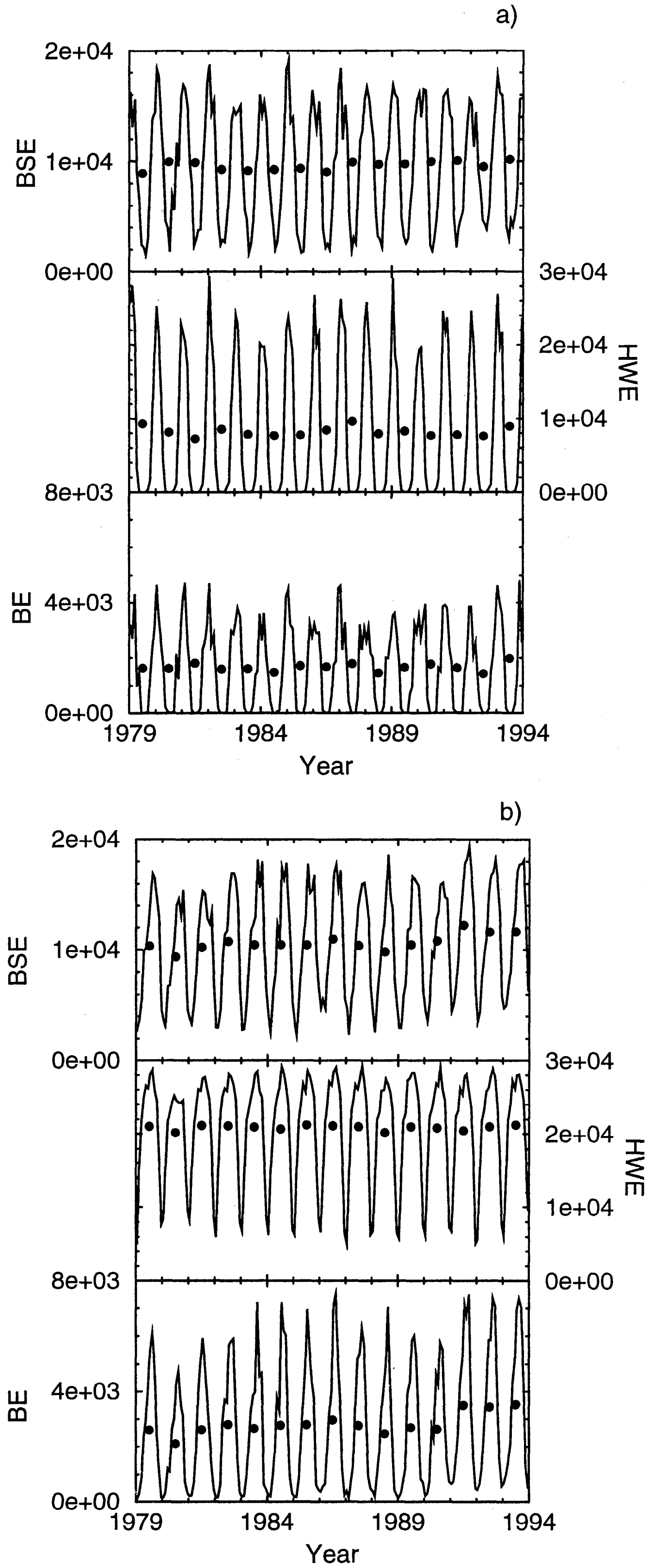

Figure 6. Monthly (solid lines) and annual (dots) trends in the number of blowing snow events (BSE), high-windchill events (HWE), and blizzard events (BE) for (a) the Northern Hemisphere and (b) the Southern Hemisphere. Yearly values have been normalized by a factor of 12 for comparison with the monthly frequencies of events.

Table 3. Average Annual Number of Blowing Snow Events (BSE), High-Windchill Events (HWE) and Blizzard Events (BE) in the Northern Hemisphere (NH), the Southern Hemisphere (SH), and the Globe for the Period 1979-1993

Type of Event	NH		SH		Globe	
	$\times 10^5$	%	$\times 10^5$	%	$\times 10^5$	%
BSE	1.152	6.17	1.279	6.85	2.432	6.51
HWE	0.983	5.27	2.502	13.40	3.485	9.33
BE	0.198	1.06	0.338	1.81	0.537	1.44

Percentile values indicate the frequency of events on a yearly basis over all grid points and times, i.e., the actual divided by the total possible number of events.

ries are presented for each hemisphere, and the monthly trends display peaks in the number of events during each hemispheric winter. In the NH, monthly frequencies attain a maximum typically between January and March, while in the SH the maxima are reached usually between July and September. Note the absence of high-windchill and blizzard events in the NH during its summer, whereas the SH experiences these episodes year-round due to the colder summertime temperatures over Antarctica compared to those of the polar NH summer.

By observing the annual trends, we see that about an equal number of blowing snow events occurs in the NH and the SH but that considerably more high-windchill and blizzard events take place in the SH (Figure 6). Interannual variability is also evident in the yearly trends of blowing snow and blizzard events, but the number of high-windchill events is nearly constant in the SH. Table 3 lists some of the absolute and relative values of the frequencies of all three types of events. We see that, on average, the number of occurrences is of the order of 10^5 annually for the original latitude/longitude grid used in this study. High-windchill events are more common than blizzard events despite the higher WC criterion for the former relative to the latter. This is due to the strict wind speed threshold imposed in the definition of a blizzard event, whereas a high-windchill event is not required to satisfy a critical value of either T_a or U_{10}, as long as $WC > 2.0$ kW m^{-2} (see section 2).

Anomalies in blowing snow, high-windchill, or blizzard events may be due to several factors, including SLP, air temperature, and wind speed fluctuations, all factors affecting these processes. Figure 7 depicts ar-

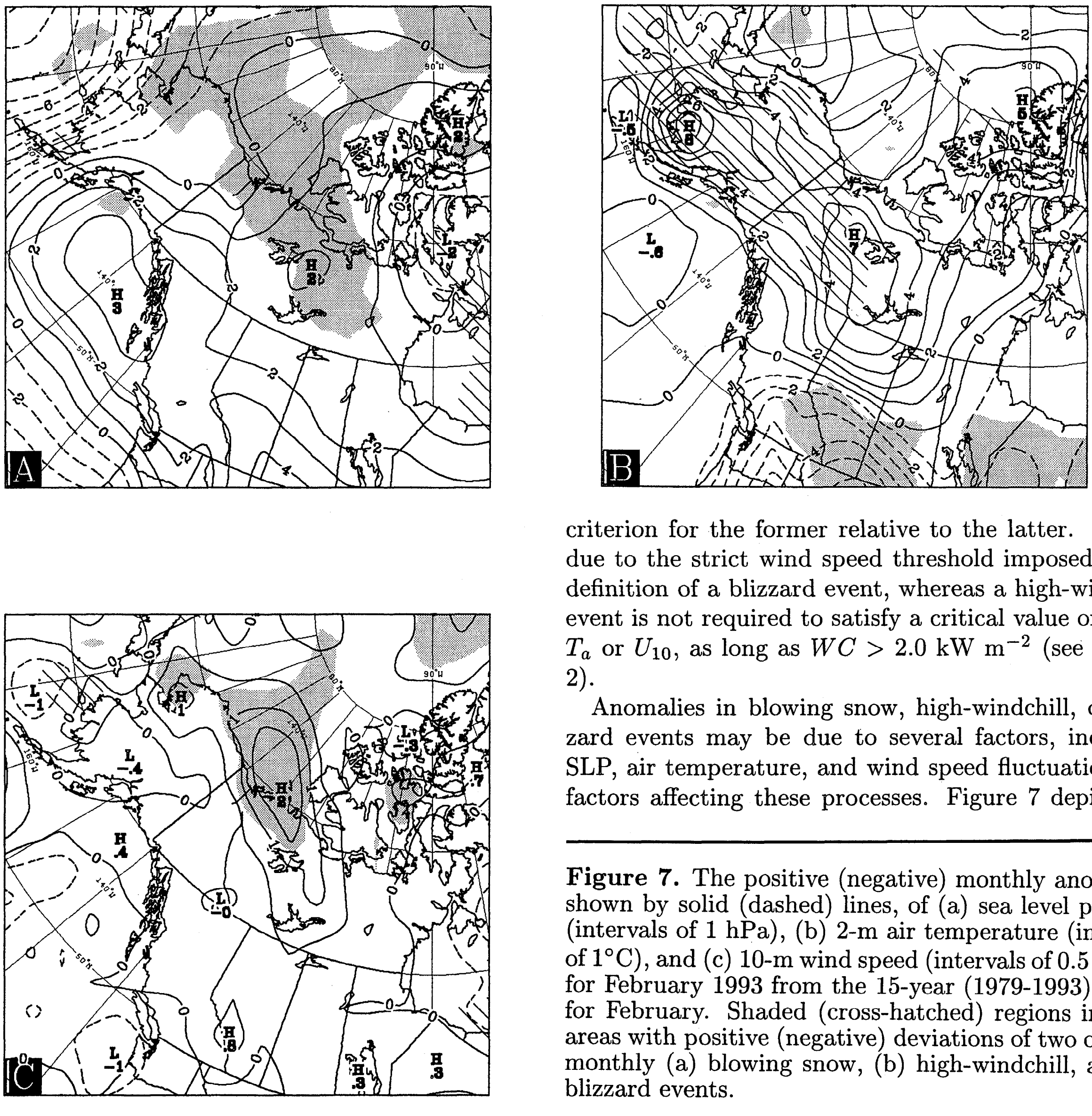

Figure 7. The positive (negative) monthly anomalies, shown by solid (dashed) lines, of (a) sea level pressure (intervals of 1 hPa), (b) 2-m air temperature (intervals of 1°C), and (c) 10-m wind speed (intervals of 0.5 m s^{-1}) for February 1993 from the 15-year (1979-1993) means for February. Shaded (cross-hatched) regions indicate areas with positive (negative) deviations of two or more monthly (a) blowing snow, (b) high-windchill, and (c) blizzard events.

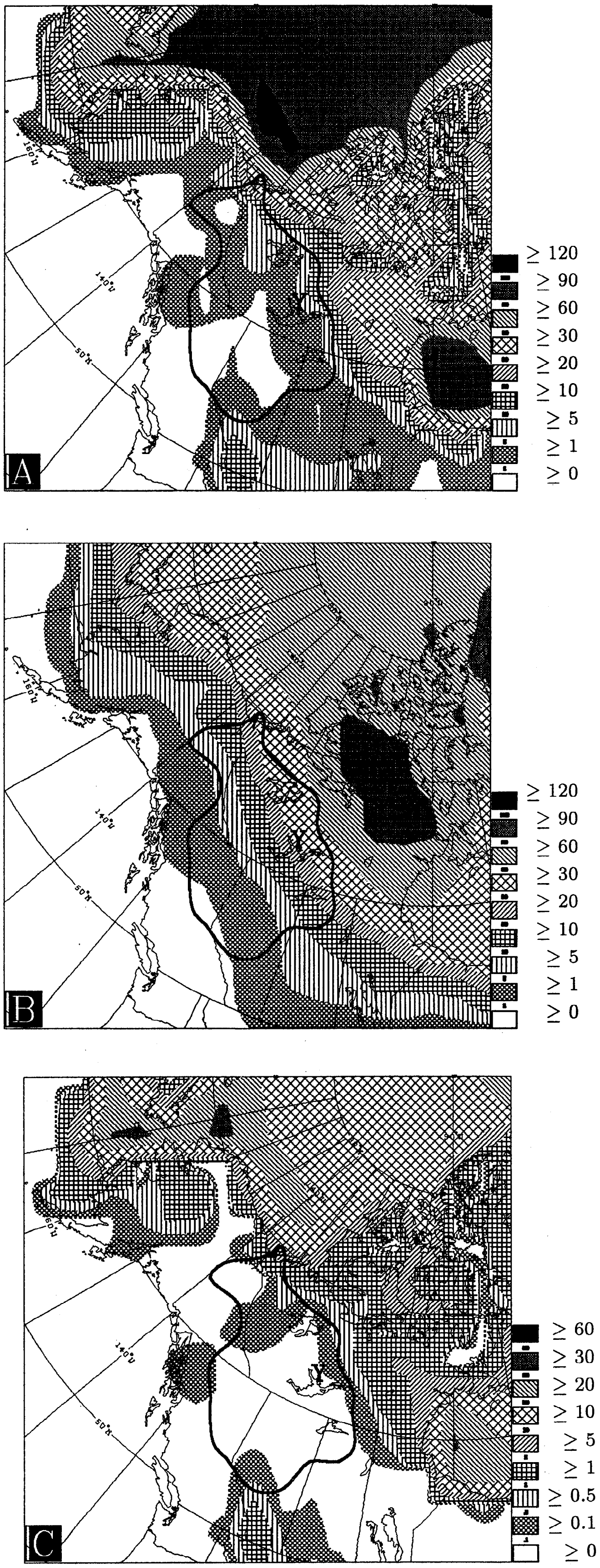

Figure 8. Mean annual frequency of (a) blowing snow, (b) high-windchill, and (c) blizzard events in the Mackenzie River Basin (denoted by the thick line) for the period 1979-1993.

eas that experienced in 1993 positive and negative deviations of at least two or more blowing snow, high-windchill, and blizzard events from the 15-year mean for the month of February in the vicinity of the MRB. Clearly associated with the positive blowing snow and blizzard event anomalies are significant deviations in U_{10} (up to 2 m s^{-1} from the monthly average) with noticeable positive T_a fluctuations nearby. This confirms that a strong correlation exists between wind speed and blowing snow and blizzard event anomalies. We also observe an SLP anomaly of 2 hPa from the climatological mean centered over the MRB. The near-surface air temperature is a more critical parameter for the number of high-windchill events as positive (negative) deviations in frequency are collocated with negative (positive) temperature fluctuations.

4.3. Climatology for the Mackenzie River Basin

4.3.1. Frequency of events. We now emphasize the climatology of significant winter-type weather events for the MRB, which is the area of interest of MAGS (Figure 1). The MRB drains approximately one fifth of the Canadian landmass and is situated in an area where wintertime processes are important [*Lawford*, 1993, 1994]. Although most of it is forested, the northeastern and northern sections of the basin lie within Arctic tundra. These barren lands are conducive to frequent blowing snow events (≥ 10 per year) which decline rapidly in number within the taiga, where fewer than five annual episodes occur (Figure 8a). The number of occurrences begins to increase southward as the boreal forest gives way to the open prairies. In comparison to *Phillips* [1990], we underestimate the frequency of blowing snow events in the forested regions of the MRB, where the ERA displays a negative wind speed bias (Table 2).

High-windchill events are also most common over the Arctic tundra (Figure 8b). Near the southernmost sections of the basin, no more than a few days per year with $WC \geq 2.0$ kW m^{-2} are expected. However, the number of events increases moving to the northeast such that as many as 60 high-windchill events occur over the cold Arctic tundra, which evidently coincides with the area of highest blizzard frequency (Figure 8c). Blizzards are uncommon in most sections of the MRB; nonetheless, perhaps one such storm may affect the lower Mackenzie Valley every 2 years, whereas the coastal regions may expect more than five events annually. These results confirm the conjecture by *Stewart et al.* [1995a] that two blizzard regimes exist in the NVT and NWT of Canada, with the areas of high and low frequencies delineated by the treeline.

4.3.2. Forcings of events. Compositing is an averaging technique used to reveal atmospheric patterns common to a meteorological event. The method has been applied, for instance, to detect synoptic- or planetary-scale signatures of widespread heavy precipi-

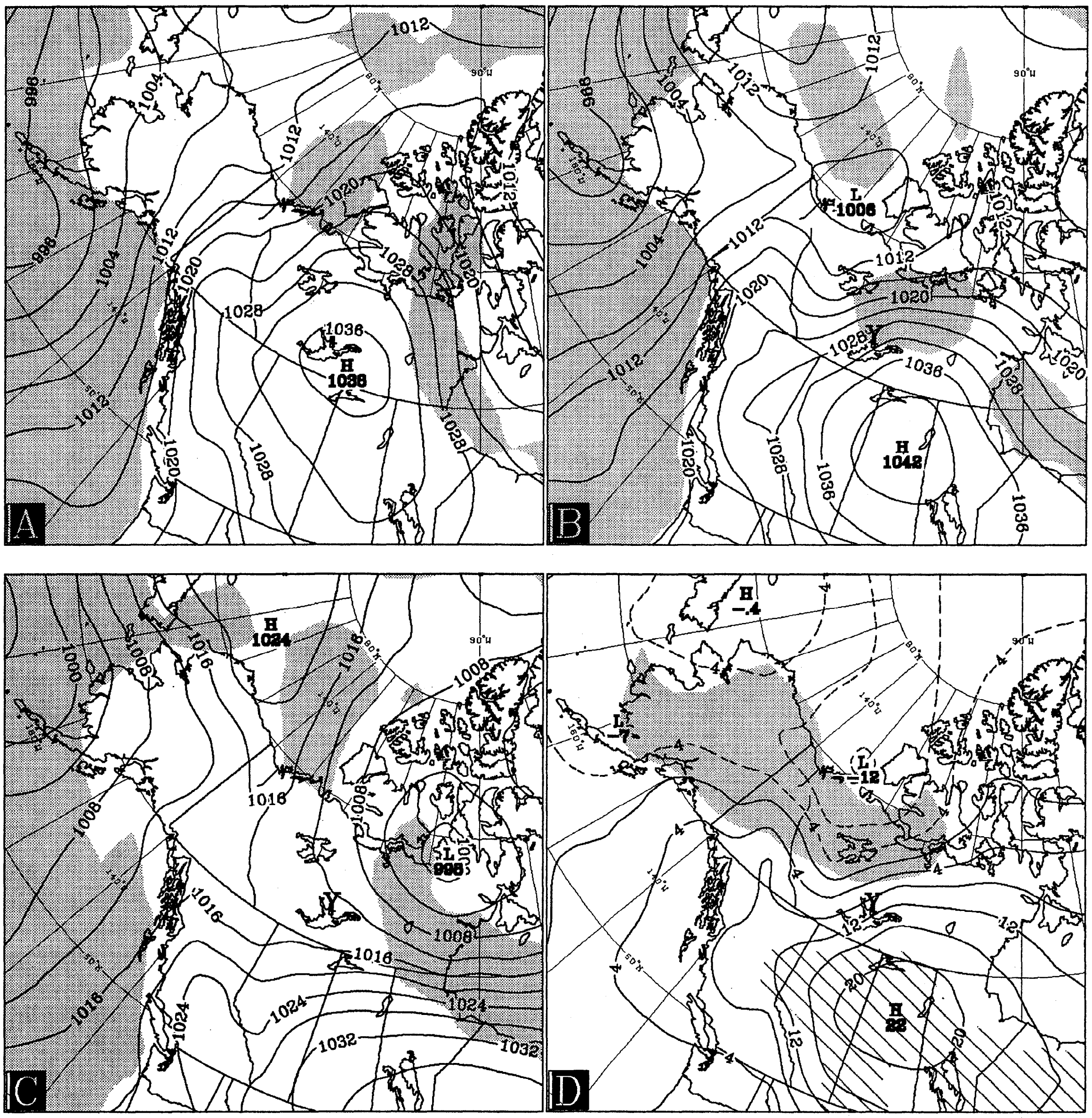

Figure 9. Composites of the sea level pressure at 4 hPa intervals (a) 24 hours prior to (T−24), (b) during (T00), and (c) 24 hours after (T+24) 11 blowing snow events associated with winds from the SW quadrant near Yellowknife (denoted by "Y"). Shaded areas denote 10-m wind speeds >6 m s^{-1}. Positive (negative) deviations from the 15-year climatological mean sea level pressure (hPa) during the events (T00) are shown in Figure 9d in solid (dashed) lines with 2-m air temperature anomalies of >5°C (< −5°C) from the 15-year climatological mean shaded (cross-hatched).

tation episodes in the MRB [*Lackmann and Gyakum*, 1996]. Given that our primary interest lies in snow transport, we apply the technique at a particular location by averaging the fields of SLP, surface temperature, and wind speed during blowing snow events. Some preliminary tests revealed that stratification of the events with respect to wind direction yielded superior results. We therefore classify blowing snow events into four categories, depending on the wind direction quadrant, i.e. (winds from the) SW, NW, NE, and SE quadrants. The results shown here are for blowing snow events that occurred during the months of January to March 1979 to 1993, inclusive, near Yellowknife, NWT (62°28′N, 114°27′W), chosen for its central location within the MRB (see Figure 1). To ensure the significance of the results, we applied a Student's t test [*Wilks*, 1995] to the data. This statistical test is commonly employed in the application of the compositing technique [e.g., *Lackmann and Gyakum*, 1996], with the threshold confidence level of 95% often used to assess the validity of the results. In our case, a confidence level ≥95% limited our compositing to within ±24 hours from the time of the events.

Figure 9 is a composite of the SLP field with superimposed regions where winds ≥6 m s^{-1} when the event is occurring (T00), as well as 24 hours prior to and after the event (T−24 and T+24, respectively), while Figure 9d represents deviations of SLP and T_a from the 15-year (1979-1993) monthly climatological means at T00. Thus Figures 9a-9c show the temporal evolution of SLP and wind fields that favor southwesterly blowing snow events near Yellowknife. At T00, we observe a composite anticyclone that has moved into the Canadian prairies with central SLP of 1042 hPa and a trough in the lee of the Mackenzie Mountains and an associated cyclone to the north that lead to an enhanced SLP gradient near Yellowknife. Mean wind speeds there are about 8.0 m s^{-1} with threshold for transport, again computed following equation (1), near 7.0 m s^{-1}. Associated with these strong southwesterly winds in the MRB are positive temperature deviations of about 5°C from the climatological mean northwest of Yellowknife, while the prairies experience colder than normal conditions (Figure 9d). Subsequently, the cyclone moves eastward and intensifies along the Arctic coast of the NVT, whereas the high-pressure system has moved southeastward into the United States. Figure 9d reveals the SLP departures from the monthly climatological means at T00 responsible for the blowing snow events at Yellowknife. A decrease of up to 12 hPa in SLP to the northwest of Yellowknife, while to the southeast, an increase of up to 22 hPa in SLP from the climatological mean contributes to high wind speeds and blowing snow events near Yellowknife.

A developing anticyclone in Alaska is a dominant factor in producing blowing snow events occurring with northwesterly winds (Figure 10). This high-pressure system moves southeastward into the Yukon Territory

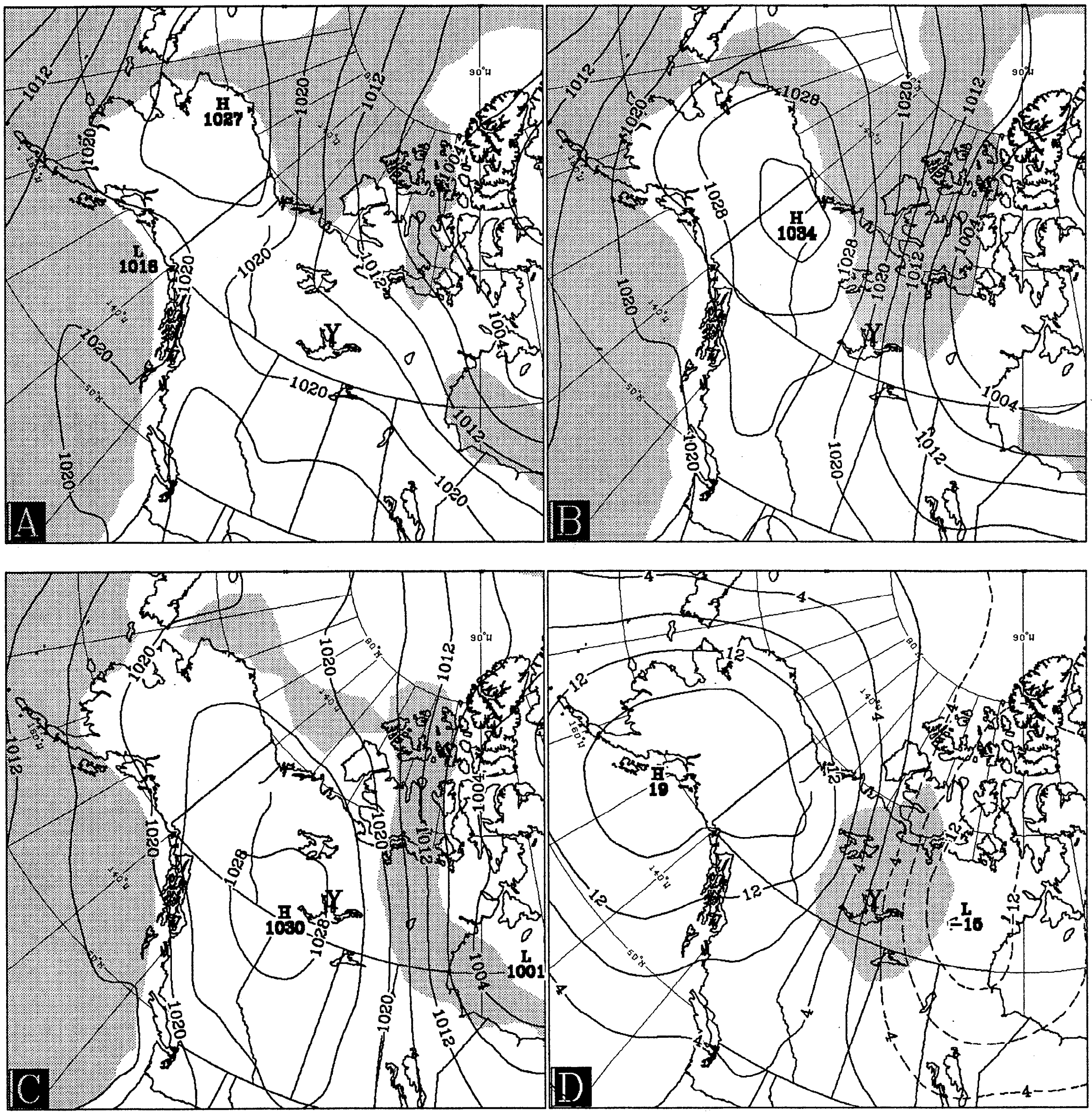

Figure 10. As in Figure 9 except for 78 blowing snow events associated with winds from the NW quadrant near Yellowknife (denoted by "Y").

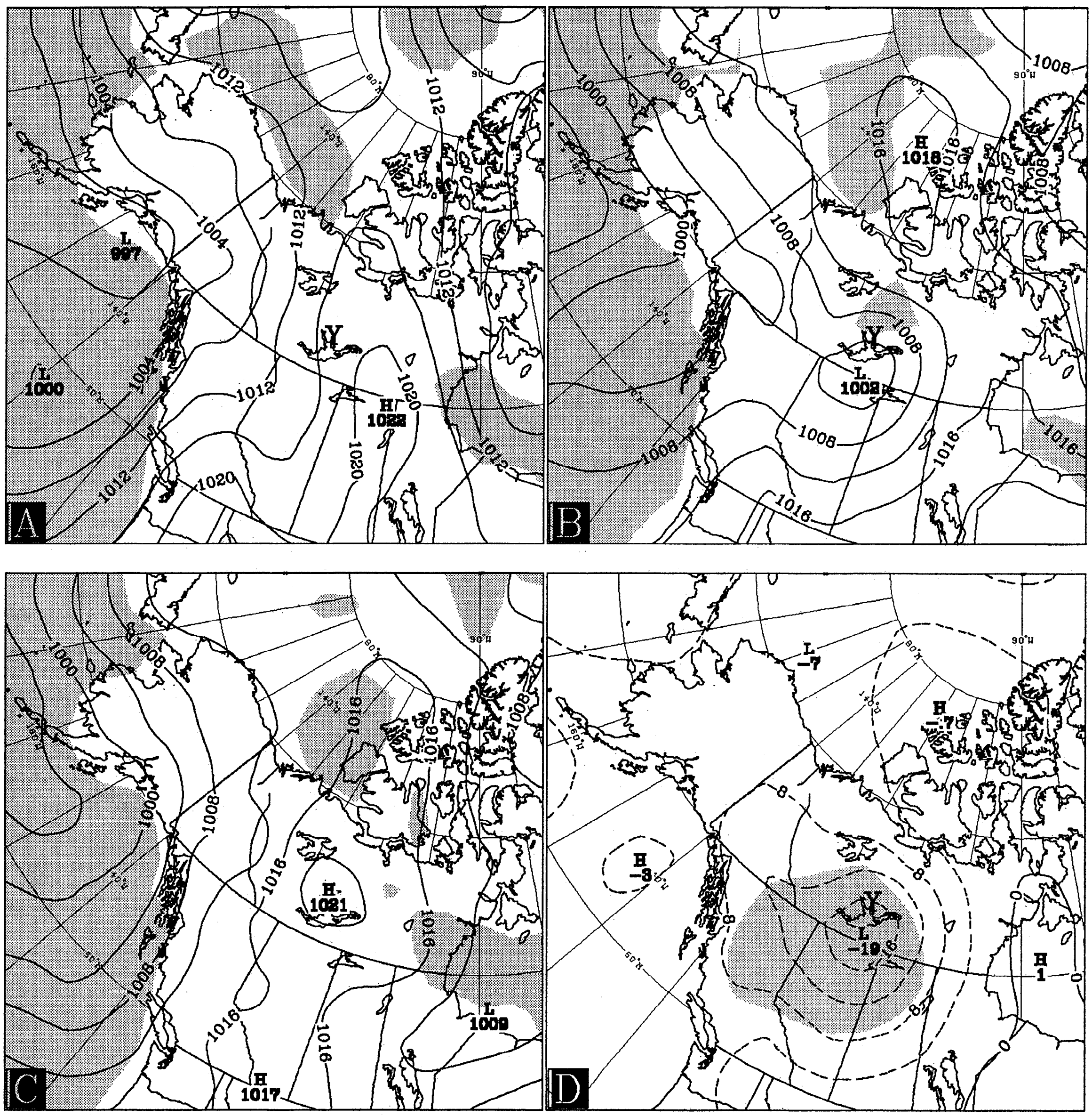

Figure 11. As in Figure 9 except for eight blowing snow events associated with winds from the NE quadrant near Yellowknife (denoted by "Y").

(YT) at T00, while a quasi-stationary cyclone remains in the Hudson Bay area. Wind speeds reach values of 8.1 m s^{-1}, again 1.0 m s^{-1} on average above the threshold, while warmer conditions than normal prevail throughout the MRB. As in southwesterly events, there is both a maximum and minimum in SLP deviations from the climatological mean; however, positive changes in SLP are to the west of Yellowknife over Alaska and the YT, while negative changes in SLP are centered over the NVT. Warmer air than usual is also found during these blowing snow events.

Strong winds from the NE quadrant occur infrequently at Yellowknife. However, the few blowing snow events associated with northeasterly winds are associated with cyclogenesis in the lee of the Rocky Mountains in Alberta. Prior to genesis (T−24), a ridge of high pressure dominates the SLP field over western Canada (Figure 11). However, a low in the Gulf of Alaska is also a prominent feature in this case as well. Troughing into the interior leads to cyclogenesis in central Alberta and blowing snow in Yellowknife. Subsequently, the low-pressure system moves quickly into Hudson Bay, allowing a high-pressure system to take its place near Great Slave Lake. In this case, only a strong decline in SLP with minimum of 19 hPa is notable, while surrounding areas experience little change in SLP from the climatological mean. The weaker SLP gradients signify that wind speeds are, on average, only 7.2 m s^{-1} for the northeasterly events, at least 0.5 m s^{-1} less than the other quadrants.

For the final sector, an anticyclone east of the Great Slave and Great Bear Lakes and an Aleutian low are

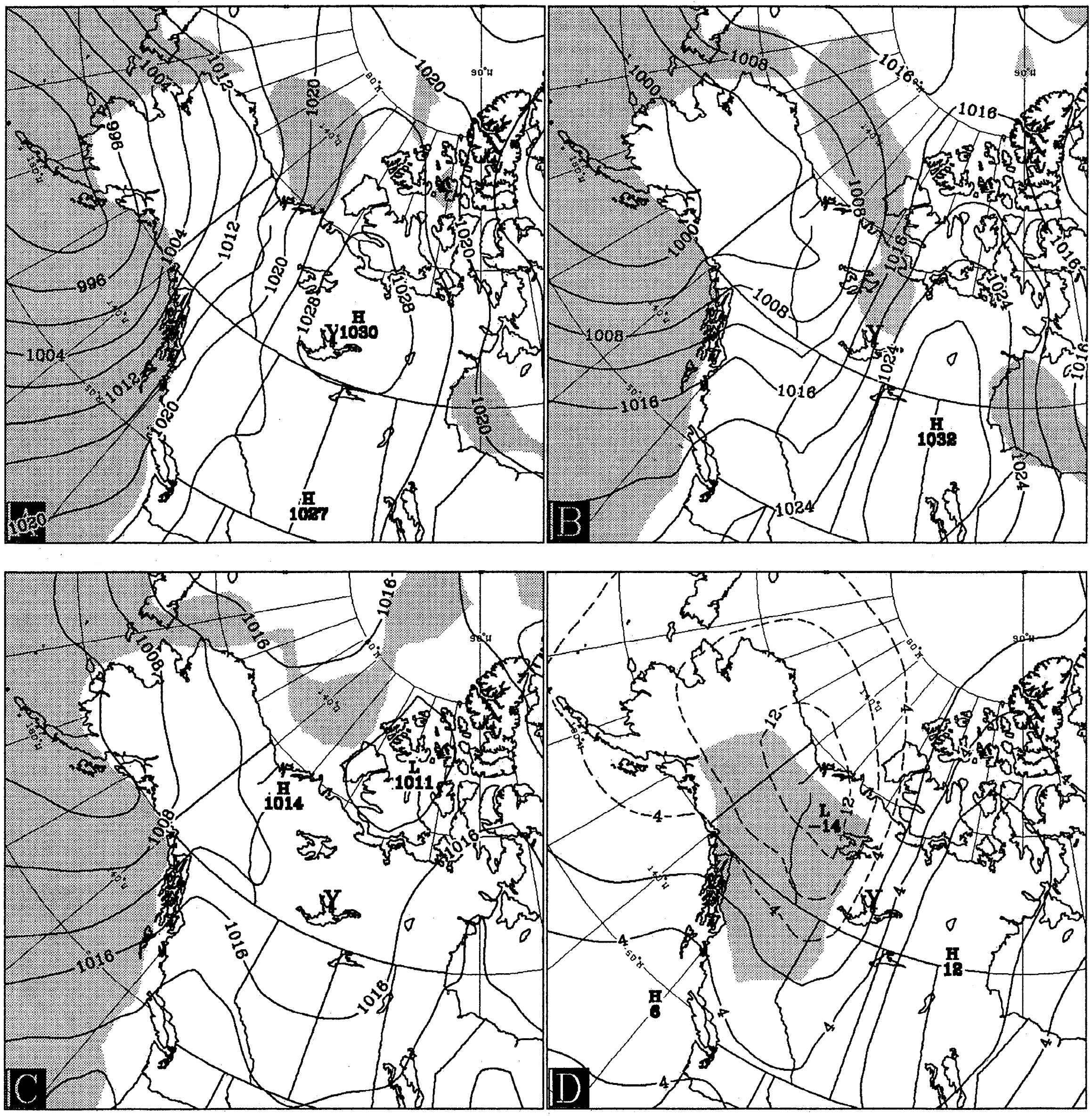

Figure 12. As in Figure 9 except for 37 blowing snow events associated with winds from the SE quadrant near Yellowknife (denoted by "Y").

initial signatures of a blowing snow event with southeasterly winds near Yellowknife (Figure 12a). This high-pressure system propagates southeastward to lie over eastern Saskatchewan, with troughing along the Mackenzie Mountains yielding lower SLPs in the northwestern section of the basin. The strong SLP gradient results in mean wind speeds of 7.8 m s^{-1} in the Yellowknife area and warmer conditions than usual in the YT. Troughing into the MRB leads to cyclogenesis, and this low moves rapidly northeastward over the Arctic Islands at T+24 as it intensifies. As in the southwesterly cases, a decrease in SLP from the climatological mean exists to the northwest of Yellowknife, while an elongated region of positive deviations in SLP is centered to the east of Yellowknife.

For the four quadrants combined, 134 blowing snow events near Yellowknife are inferred for the 15 years of the ERA data. This is an average of about nine events annually, one less than the observed long-term climatology [*Environment Canada*, 1984]. Most blowing snow events at Yellowknife are observed to occur with northwesterly winds (A. C. Giles, personal communication, 1999), as we find in our climatology.

5. Concluding Discussion

Using the gridded ERA data, we have compiled a global 15-year climatology of blowing snow, blizzard, and high-windchill events. The results confirm that the blustery ice fields and ice shelves of Antarctica and

Greenland, the ice-covered Arctic Ocean and polar seas, as well as the Arctic tundra are high-frequency zones of significant winter-type weather processes. We find that the most common type of adverse cold-season processes are high-windchill episodes which occur at 9.3% of all possible grid points and times on a yearly basis, followed by blowing snow (6.5%), and then blizzard (1.4%) events. These are controlled primarily by geography (e.g., surface cover, latitude, altitude) and meteorological variables, most notably wind speed for blowing snow and blizzard events, and air temperature for high-windchill events. In the MRB, we find similar results, as fewer events occur within the boreal forest than the neighboring prairies or Arctic tundra. Trends in the frequency of events were examined and showed both monthly and interannual variability. Stormy periods at high latitudes are likely to be accompanied by higher frequencies of blowing snow and blizzard events, whereas colder than usual conditions will produce a higher number of windchill episodes.

The compositing of the near-surface fields of SLP, temperature, and wind speed has revealed some of the synoptic-scale signatures that produce blowing snow events near Yellowknife, NWT, located centrally within the MRB. The presence of strong SLP gradients producing wind speeds >7 m s^{-1} and subfreezing temperatures are the necessary ingredients to produce blowing snow over a snow-covered surface. For the four quadrants examined in section 4.3.2, we note that intensifying anticyclones are dominant features in all but one of the four composites. Additional strengthening of the SLP gradient is provided by troughing and cyclogenesis in the lee of the Mackenzie Mountains for SW and SE events and of the Rocky Mountains for NE events, while a quasi-stationary low over Hudson Bay is critical for NW events. These features lead to deviations in SLP from the monthly climatological means that show a "dipole" structure in three out of the four composites, with Yellowknife sandwiched between an area of positive and negative SLP departures. A similar dipole feature was also observed by *Lackmann and Gyakum* [1996] in 500 hPa geopotential height anomalies in their study of high-precipitation events in the MRB. Thus strong departures from the climatological mean SLP or 500 hPa geopotential heights in the vicinity of Yellowknife are conducive to adverse meteorological conditions there. We also noted positive temperature deviations from the climatological means near or at Yellowknife in all four composites. The prevalence of cold anticyclones and accompanying calm weather in this region during winter indicates that stormy periods are generally associated with warmer than average temperatures in the MRB.

The results in this paper have focused on the frequency of blowing snow events, since the water budget of nival regimes can be influenced by two related processes: (1) the redistribution of snow by wind can lead to significant erosion of mass in open, windswept areas and accumulation in others and (2) the concurrent transfer of ice particles to water vapor during transport can lead to further snowpack depletion. A number of recent studies have assessed the contribution of these processes to the surface mass balance, with significant variation on the importance of the blowing snow sublimation component [*King et al.*, 1996; *Pomeroy et al.*, 1997; *Bintanja*, 1998]. To that effect, *Déry and Taylor* [1996] and *Déry et al.* [1998] have developed a blowing snow model named PIEKTUK that considers the negative thermodynamic feedbacks of the blowing snow sublimation process in the ABL. They conclude that in some circumstances this process is self-limiting, thus supporting studies that yield lower estimates of the blowing snow sublimation component to the surface water budget. With blowing snow occurring rarely over the forested areas of the MRB, the water budget for the basin will not likely be affected if storms and strong wind conditions are confined to the southern portion of the MRB. However, when storms and strong wind conditions affect the northern part of the basin occupied by Arctic tundra, the blowing snow component may not be negligible. We are presently coupling a modified version of PIEKTUK to the Mesoscale Compressible Community (MC2) model [*Benoit et al.*, 1997] to provide more accurate evaluations of the importance of blowing snow in the cold-season water budget of such regions.

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