An Empirical Blowing Snow Forecast Technique for the Canadian Arctic and the Prairie Provinces

DAVID G. BAGGALEY

Prairie and Arctic Storm Prediction Centre, Meteorological Service of Canada, Winnipeg, Manitoba, Canada

JOHN M. HANESIAK

Centre for Earth Observation Science, Faculty of Environment, University of Manitoba, Winnipeg, Manitoba, Canada

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ABSTRACT

Blowing snow has a major impact on transportation and public safety. The goal of this study is to provide an operational technique for forecasting high-impact blowing snow on the Canadian arctic and the Prairie provinces using historical meteorological data. The focus is to provide some guidance as to the probability of reduced visibilities (e.g., less than 1 km) in blowing snow given a forecast wind speed and direction. The wind character associated with blowing snow was examined using a large database consisting of up to 40 yr of hourly observations at 15 locations in the Prairie provinces and at 17 locations in the arctic. Instances of blowing snow were divided into cases with and without concurrent falling snow. The latter group was subdivided by the time since the last snowfall in an attempt to account for aging processes of the snowpack. An empirical scheme was developed that could discriminate conditions that produce significantly reduced visibility in blowing snow using wind speed, air temperature, and time since last snowfall as predictors. This process was evaluated using actual hourly observations to compute the probability of detection, false alarm ratio, credibility, and critical success index. A critical success index as high as 66% was achieved. This technique can be used to give an objective first guess of the likelihood of high-impact blowing snow using common forecast parameters.

1. Introduction

The central arctic experiences the most occurrences of blowing snow in Canada, while the Canadian prairies have significant number of events as well (Phillips 1990). Blowing snow can be a hazard to public safety and transportation because of poor visibility associated with some events. An accurate forecast of the occurrence and resultant visibility of this phenomenon may help to mitigate this hazard. Unfortunately, predicting the occurrence of blowing snow and the associated reduction in visibility is difficult due to complexities related to snowpack state and its interaction with the lower atmosphere. Blowing snow occurs when the wind shear stress exceeds the snow particle resistance to dislocation (Li and Pomeroy 1997a). Thus, the occurrence of blowing snow will vary spatially and temporally with most of the variation attributable to differences in wind speed, air temperature, and characteristics of the snow.

Corresponding author address: David G. Baggaley, Prairie and Arctic Storm Prediction Centre (PASPC), Meteorological Service to Canada, 123 Main Street, Suite 150, Winnipeg, MB R3C 4W2, Canada.
E-mail: david.baggaley2@ec.gc.ca

Although there have been several studies devoted to blowing snow from a climatological, hydrological, or pure research perspective (e.g., Lawson 2002; Li and Pomeroy 1997a, Li and Pomeroy 1997b; Dery and Yau 2001), there remains a need for a practical forecast method of the phenomenon. Pomeroy and Male (1988) developed a scheme for estimating the reduction of visibility due to blowing snow; however, it is dependent upon parameters that are in most cases not known to the forecaster (e.g., drift density and mean particle radius). Li and Pomeroy (1997b) included agricultural stubble height and local fetch distances as predictors but these elements vary on a scale smaller than usually considered by a weather forecaster. Li and Pomeroy (1997b) defined the frequency of occurrence of blowing snow for any given wind, temperature, and snowpack age as the ratio of the number of events with blowing snow divided by the number of events without. However, the utility of a forecast can be harmed by "crying wolf" or forecasting too many false alarms. This present paper attempts to put more emphasis on the false alarm aspect by defining a credibility factor. This study is aimed at creating a practical technique for the prediction of significant blowing snow and the associated visibility reductions through available observational data.

From an operational forecasting perspective, the definition of "significant" blowing snow varies with the application. For instance, a public weather forecast is mainly concerned with visibility less than 1 km, whereas the aviation industry operates using established visibility thresholds including 0.8, 1.6, 3.2, 4.8, and 8 km (½, 1, 2, 3, and 5 mi).

Knowledge of snow state and meteorological conditions are required to forecast blowing snow. While detailed snowpack properties are not typically available to the weather forecaster in real time, a record of snow depth, time since last snowfall (proxy for snow age), and interim weather conditions should be known.

The paper first discusses the historical meteorological station data that were used in this study and the methods employed to develop the blowing snow forecast scheme (section 2). Section 3 tests the ability of the scheme to forecast blowing snow and visibility at various Canadian arctic and the Prairie provinces stations, with concluding remarks to follow in section 4.

2. Data and methods

a. Historical meteorological observations

The Environment Canada weather stations (Fig. 1) were selected based on the completeness of their observational record, their proximity to large population centers, and aviation terminal weather forecast locations. Hourly weather observations (air temperature, wind direction, mean wind speed, prevailing visibility, and precipitation) dating from 1960 to 1999 were used from each station. Prevailing visibility is defined as the maximum visibility value common to sectors comprising one-half or more of the horizon circle (Atmospheric Environment Service 1977). Wind gust data were also included in a portion of the database. Intermediate observations, or "specials," were not available. Some stations in the arctic reported weather every 3 h in the early 1960s. Consequently, the portions of observations with incomplete records at these particular stations were omitted from this study. Observations from October to April were selected as most blowing snow events occur over these months (>95%).

Blowing snow is defined as snow particles raised by wind to sufficient heights above the ground to reduce horizontal visibility to 9.7 km (6 mi) or less (Atmospheric Environment Service 1977). Horizontal visibility is measured at 1.8 m above the ground. Visibilities recorded during periods of darkness were modified in this study. Rasmussen et al. (1998) found that visibility is reduced to a lesser degree at night compared to daylight hours for the same rate of falling snow. By analogy, this process was applied to visibilities in blowing

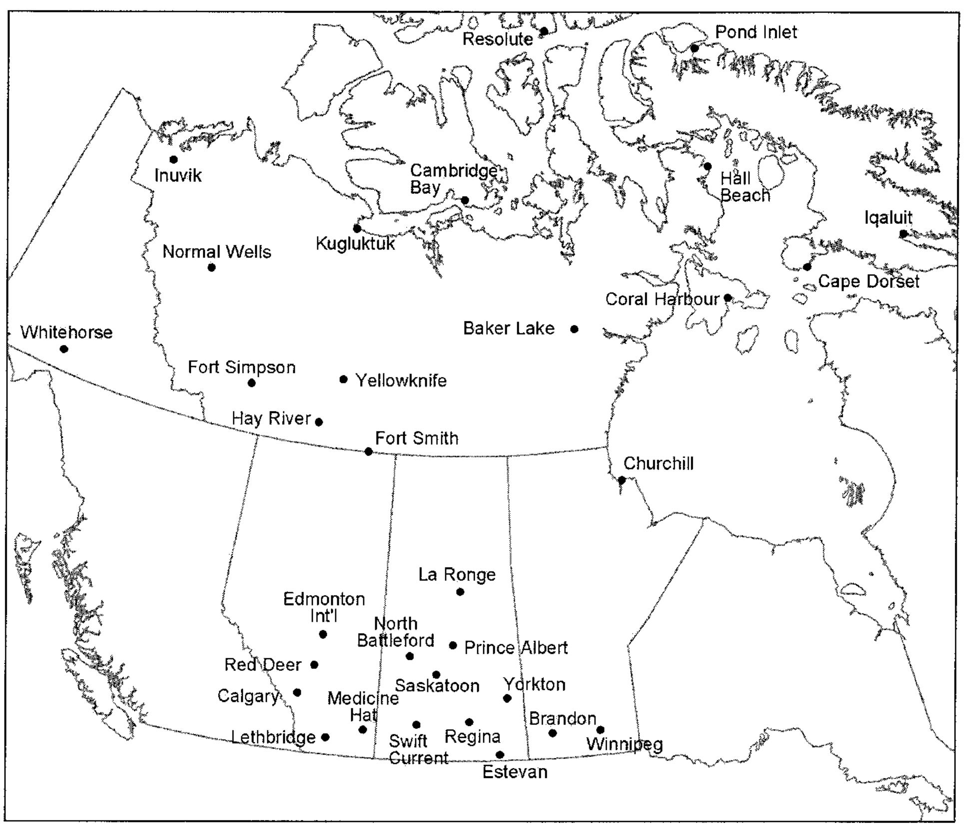

FIG. 1. Locations of the observational sites.

snow. Sunrise and sunset times were calculated for each station based on date, latitude, and longitude. A daytime equivalent visibility was calculated for snow and/or blowing snow by multiplying nighttime visibilities by a factor of 2/3 (Rasmussen et al. 1998).

The height of the anemometer affected the reported wind speed. Most stations had a variety of anemometer heights over the course of the record but were eventually remounted at the current standard 10-m level. All wind speeds were corrected to a 10-m standard according to Davenport (1960):

$$U_{10} = U_h(10/h)^{0.20}, \tag{1}$$

where U_{10} is the wind speed at 10 m, U_h is the reported wind, and h is the height of the anemometer.

An attempt was made to test if wind gusts can influence the occurrence of blowing snow by the application of additional kinetic energy to the snow surface. Some observations report both mean wind and gusts, while the rest have just mean winds. As a consequence, an equivalent wind, U_{eq}, was developed to compare gusty winds to steady state winds by relating their energy content. Using the simplest case of a wind increasing linearly in speed over a unit time, t, we can define $U_{diff} = (U_{max} - \overline{U})$ and $U_{min} = (\overline{U} - U_{diff})$. Thus, the instantaneous wind speed (u) over one cycle (i.e., from U_{min} to U_{max}) would be

$$u = U_{min} + 2U_{diff}t. \tag{2}$$

The power of the wind is proportional to the velocity cubed (Elliot 1986). Given that the energy of the wind is power multiplied by time, the relative wind energy, *E*, over one cycle would be

$$E = \int_{t=0}^{1} u^3 dt \tag{3a}$$

$$E = \int_{t=0}^{1} (U_{min} + 2U_{diff}t)^3 dt \tag{3b}$$

$$E = U_{min}^3 + 3U_{min}^2 U_{diff} + 4U_{min}U_{diff}^2 + 2U_{diff}^3. \tag{3c}$$

The equivalent mean wind, U_{eq}, which is the steady-state wind speed that has the same energy content as the gusty wind, would be

$$U_{eq} = \sqrt[3]{E}. \tag{3d}$$

For illustration, a reported hourly mean wind of 20 km h^{-1} gusting to 40 km h^{-1}, where it is assumed that wind cycles from 0 to 40 km h^{-1}, has the same energy as a steady wind of 25 km h^{-1}. While this assumption oversimplifies the chaotic nature of gusty winds, subsequent testing indicated that this adjustment showed an improvement over the unmodified mean wind speed.

Based upon previous snow work done by Jordan et al. (1999) and Hanesiak et al. (1999), the daily maxima net radiation on the snow surface are better reflected in maximum daily temperatures. The latter would therefore have more influence on the aging of the snowpack than the temperature at the time of the blowing snow event, which in turn should influence the blowing snow processes. The highest temperature since the last snowfall was used as an independent variable in our analysis.

Thus the reported wind speed may be adjusted for anemometer height, gustiness, and/or temperature. Incorporating station barometric pressure will affect air density and should therefore have some theoretical influence on blowing snow. Testing did not show any measurable difference, and would represent a complication to the forecasting process. Thus, the effect of barometric pressure was not incorporated into any of the results.

b. *Analysis and forecast scheme*

To test whether or not regional differences were important, all of the observations from arctic[1] stations were combined and compared to a collection of reports from the Prairie provinces. Blowing snow events were divided into observations with and without concurrent precipitating snow. For observations with blowing snow with visibility 1 km or less in the Prairie provinces, 77.9% occurred with precipitating snow, whereas in the arctic this figure was just 31.9%. The blowing snow events that occurred without concurrent falling snow (ground blowing snow) were grouped by snow age. Since the likelihood of blowing snow decreased with time after the last occurrence of falling snow, the time span of each age group was set larger at greater ages (e.g., the age groups were set to 1–2, 3–5, 6–11, 12–23, . . . 192–383 h since last snowfall). It was found that this grouping scheme maintains a reasonable sample size in each snow age group.

There were a few cases of blowing snow with extremely old snowpacks (>1 month), or with snowpacks that had undergone liquid precipitation or significant melting. We suspect these cases to be blowing snow being advected from a distant location, but this could not be determined using point observational data. To reduce the effect of advected blowing snow on the results, all positive events and nonevents that occurred after a melting period with temperatures greater than 4°C (<5% of the total hits) were excluded in the calculations. Similarly, all observations that occurred after liquid precipitation were discarded. Individual reports that included fog, smoke, blowing dust, or ice pellets were removed from the dataset.

Site-specific topography may preclude blowing snow

[1] Arctic stations are all north of 60° north latitude. Churchill, Manitoba, was also treated as an arctic station.

with certain wind directions at particular observation sites. A climatology of blowing snow events was derived for each station and for each wind direction (in tens of degrees) with and without concurrent precipitating snow. A similar climatology can be found in Hanesiak et al. (2003). If there were no cases of blowing snow from a certain wind direction at a particular location, null events from that direction and location were also removed from the analysis. Since blowing snow is much less common in forested areas than in the open prairies, stations such as La Ronge, Saskatchewan, contributed very little to the final statistics. A forecaster may mimic this process by checking the climatology or the characteristics of the terrain and vegetation of a particular site before predicting the occurrence of blowing snow (Hanesiak et al. 2003).

Some hourly reports with a given wind and snow character occurred with significant blowing snow while other instances of similar circumstances did not. To provide a measure of the proportion of occurrences of significant blowing snow with a given set of environmental conditions, a credibility (CRED) quantity was extracted from the dataset:

$$\mathrm{CRED} = p/(p + n), \tag{4}$$

where p is the number of positive events and n is the number of nonevents (each defined below). CRED varies from 0 to 1. A CRED of 0 means no cases of blowing snow were observed for the given wind, temperature, and snowpack properties, while a CRED of 1 says all situations of that type had blowing snow. CREDs between 0 and 1 reflect the confidence that the expected conditions will produce blowing snow. A forecaster must be aware of the dangers of "crying wolf" or producing to many false alarms. It was for this reason that CRED was used as opposed to a simple ratio of events and nonevents. CRED was calculated from the observational data for wind speed (every 1 m s^{-1} up to 40) and temperature by every degree from +4 to −40°C.

With concurrent precipitating snow, a positive event is defined as any hourly report of visibility less than or equal to a given specified threshold (public or aviation limits) with observed light snow and blowing snow. A nonevent is defined as any hourly observation with reported light snow, but with visibility greater than the specified threshold. The latter group may contain reported blowing snow provided the visibility remains greater than the threshold. Light snow is defined as falling snow giving visibility greater than or equal to 1.01 km (5/8 mi). Observations with moderate and heavy snow were excluded, as this precipitating snow would give low visibility whether or not blowing snow occurred. These definitions also apply to cases without concurrent precipitating snow except that the hourly observations will not include any falling snow.

The frequency of blowing snow at a given temperature and snowpack age has a cumulative normal probability distribution (Li and Pomeroy 1997b). Similarly, CRED also has a similar distribution, such that

$$\mathrm{CRED}(U_i, T, g) = \frac{1}{\delta\sqrt{2\pi}} \int_0^{u_i} e^{-\frac{(\overline{U}-U_i)^2}{2\delta^2}}\, dU, \tag{5}$$

where U_i is the wind speed, T is the air temperature, g is the age group of the snowpack, and $\overline{U}$ and δ^2 are the mean and variance of the wind speed, respectively.

The mean and variance of this probability function was calculated at each temperature using an automated iterative method that found the best fit to the observed CRED (Fig. 2). Critical wind speeds at the 5%, 50%, and 95% CRED were computed at each temperature with Eq. (5) using the best mean and variance. The individual critical wind speeds were replotted over the range of tested temperatures and the best-fit quadratic lines at each of the 5%, 50%, and 95% CRED were derived using standard statistical software (Fig. 3).

The thresholds represented by the 5%, 50%, and 95% CREDs wind speeds represent a historic correlation but could be used as a nomogram for predicting upcoming blowing snow events. The estimate of CRED can be obtained by applying the expected temperature and wind speed. This value of CRED could then be used as an indicator of the probability of blowing snow in the future. It also shows how sensitive the likelihood of blowing snow can be to the speed of the wind. Small differences in wind speeds within the 5%–95% limits can produce large variations in the CRED. Wind speeds outside of these limits are not so critical.

In summary, the CRED of significant blowing snow occurrence was calculated over a range of temperatures and wind speeds extracted from the quality-controlled observations. Critical wind speeds were interpolated from a probabilistic function that was best fit to the observed CRED points at each temperature. Other best-fit equations then described these critical wind speeds over a range of temperatures. The result was an entirely objective estimate of the critical winds associated with significant blowing snow. This process was repeated for every permutation of

- snowpack age groups;
- specified visibilities of 0.8, 1.0, 1.6, 3.2, 4.8, and 8 km;
- using just the mean wind, and also by incorporating the mean wind and gust as available;
- all stations aggregated together, and as two groups divided as stations from the arctic and those from the Prairie provinces; and
- using T_{Current} versus using T_{Max} for ground blowing snow.

The number of combinations is large and precludes including all the graphs in this paper. Figure 3 is one example of a critical wind nomogram.

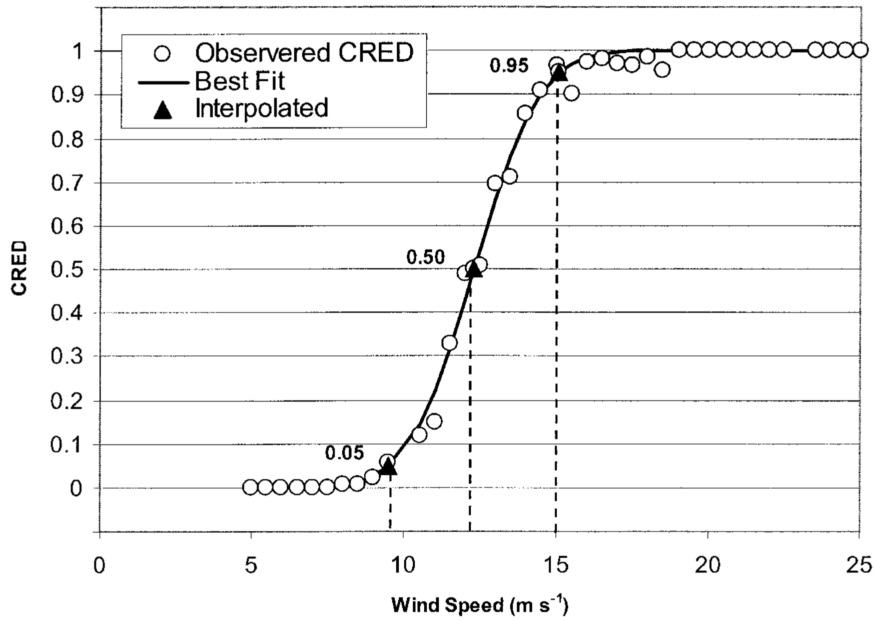

FIG. 2. Sample CRED distribution at a temperature of −20°C for all ground blowing snow cases combined showing a best-fit line (mean of 12.3 m s^{-1} and a variance of 1.7). The wind speed at the 5% CRED is interpolated to be 9.5 m s^{-1}. The wind speeds at 50% and 95% CREDs are also extracted from this curve.

3. Results and discussion

a. Blowing snow frequency

Four arctic stations (Baker Lake, Coral Harbour, Resolute Bay, and Hall Beach) account for over half the blowing snow events of the entire test group. Some of this is explained by the length of the arctic cold season. Each site in the full test group will have local effects caused by terrain and land usage that will affect the occurrence of blowing snow. To test the overall

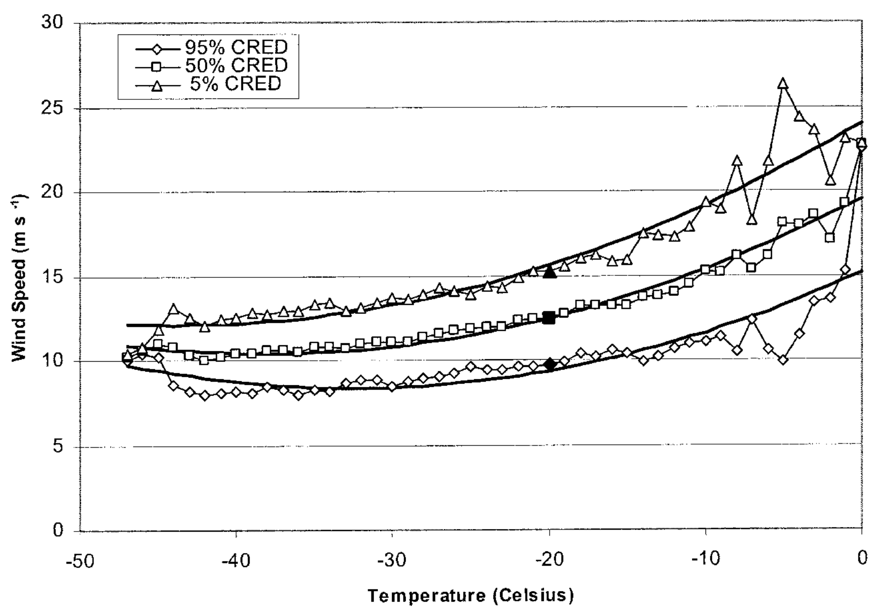

FIG. 3. The wind speeds at the 5%, 50%, and 95% CREDs from Fig. 2 are replotted (solid figures) along with those from throughout the temperature range. Best-fit quadratic lines are then inferred. This sample chart covers all ground blowing snow cases giving visibility restrictions of 1 km or less using data from both the arctic and the Prairie provinces.

TABLE 1. Pearson moment correlation coefficient of blowing snow occurrence visibility ≤ 1 km and the character of the wind for compass directions in tens of degrees.

Dataset	Method	All blowing snow cases	Blowing snow with falling snow	Blowing snow without falling snow
All sites	Mean speed	39.2%	44.9%	33.3%
	Threshold = 0	76.4	67.9	71.5
	Threshold = 7.5 m s^{-1}	86.1	76.6	80.7
	Threshold = 5% CRED	91.4	90.5	89.4
Baker Lake only	Mean speed	87.8	75.9	86.4
	Threshold = 0	96.5	78.6	95.5
	Threshold = 7.5 m s^{-1}	98.1	77.3	97.4
	Threshold = 5% CRED	98.2	96.6	98.0

significance of these local effects, the correlation between the incidence of blowing snow and the characteristic of the wind was calculated.

The Pearson moment correlation coefficient, r (Naiman et al. 1977), was used to determine the dependency of blowing snow reports with visibilities less than 1 km on the character of the wind. The wind characteristics tested were the mean speed, and the number of occurrences of speeds above set thresholds. An r of 0 would indicate that none of the variation in the one variable could be attributed to a second while an r of 1 would indicate that there is a complete positive linear correlation between the two sets of variables.

Table 1 shows that using the frequency of any wind from a given direction (threshold = 0; Fig. 4b) shows a higher r than using the mean wind from a given direc-

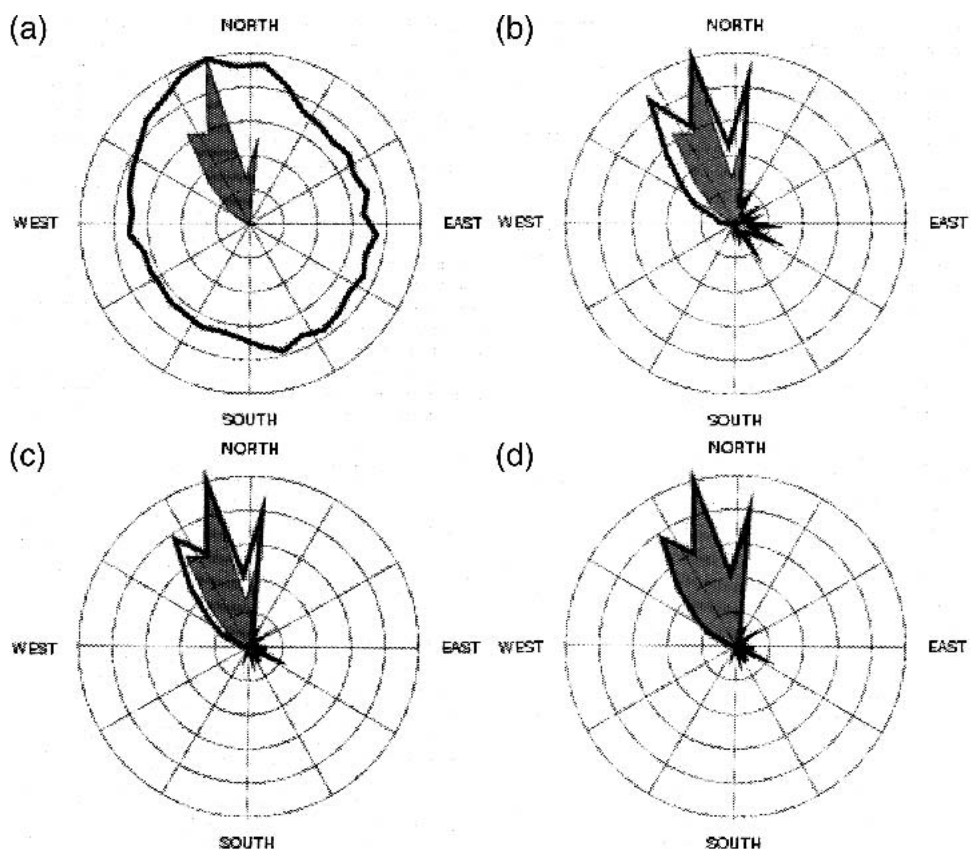

FIG. 4. The shaded areas are observed occurrences of ground blowing snow distribution by wind direction at Baker Lake of all snowpack ages and visibility ≤ 1 km. The range rings only show the relative number of occurrences by each direction in tens of degrees. The solid lines (not to the same scale) represent the distributions of the: (a) wind speed average, (b) frequency of occurrence of any wind, (c) occurrence of wind with speeds ≥7.5 m s^{-1}, and (d) occurrence of wind with mean wind equal or greater than the 5% CRED threshold. The CRED threshold was determined for each observation using the current air temperature and the formula that was derived from the arctic station database.

TABLE 2. Proportion of concurrent snow and blowing snow events that end when the precipitating snow ends.

Region	Visibility (km)	No. of snow and blowing snow events	Ending when the falling snow ends
Prairie	≤1	2087	71.3%
Prairie	≤10	4667	87.7
Arctic	≤1	3940	58.8
Arctic	≤10	7791	69.7

tion (Fig. 4a). In other words, there is a better correlation of the number of significant blowing snow events recorded at each station and direction to the number of wind occurrences from a particular direction, as opposed to the simple speed average of those occurrences. The number of strong wind events (threshold =7.5 m s^{-1}; Fig. 4c) showed a higher correlation than the frequency of winds of any speed. The number of hours with speeds above the calculated level (threshold = critical speed at 5% CRED; Fig. 4d) has a correlation of over 90% to the number of significant blowing snow occurrences for the entire sample.

The result that the best correlation occurs with winds above the CRED threshold indicates that the local topographical effects of a particular station determines significant blowing snow occurrence largely through its influence on the wind speed. Therefore, it would be valid to apply the forecast nomograms derived from this set of sites to other locations provided one could correct the forecast wind speed for the local effects of that area. Some stations in the arctic do have a high number of blowing snow events but this is mainly due to having more wind, cold temperatures, and loose snow. This may also suggest that a blowing snow climatology could be approximated for any station, provided it had a good record of temperature and wind speed (Hanesiak et al. 2003).

b. *Duration of blowing snow*

Blowing snow will cease when the wind diminishes and/or the snow becomes too compacted or all the loose snow is scoured away. In the observed events in which snow and blowing snow has occurred together, blowing snow usually terminates when precipitating snow ends (Table 2). The remaining percentage of blowing snow events that persist after the precipitating snow has ended decreases rapidly with time (Fig. 5). However, some blowing snow events in the arctic have lasted weeks after the falling snow has ended. Note that the end of an event is defined as the first report not reporting blowing snow, or reporting an improvement in visibility above the set threshold. Blowing snow may or may not have redeveloped later.

c. *Air temperature dependency of blowing snow*

As discussed by Li and Pomeroy (1997a), there is a nonlinear relationship between the frequency of blowing snow and temperature. The 5% CRED critical wind for blowing snow with concurrent precipitating snow is relatively constant over the range of temperatures (Fig. 6a). Ground blowing snow typically requires a stronger wind, especially at mild and very cold temperatures. One should expect that the critical wind would increase sharply near 0°C, but this was not always captured by the resulting curves as the number of occurrences of blowing snow drops off dramatically at temperatures near melting. The minima in critical wind speed for freshly fallen snow are at a milder temperature than for well-aged snow. Older snowpacks do not necessarily require a stronger wind to generate blowing snow compared to fresh snow. The graphs even suggest less wind is required for older snowpacks at some temperatures. Keep in mind that there were a limited number of cases of blowing snow with well-aged snowpacks (>192 h since last snowfall) and even fewer of these with temperatures near 0°C. The arctic does experience long periods of cold and darkness that can contribute to a slow aging process for the snowpack. There were almost no blowing snow events with well-aged snowpacks in the record from the Prairie provinces. Figure 6b shows that blowing snow with lower specified visibilities consistently requires stronger winds through the whole range of observed temperatures.

Figure 7a shows a simple count of reports of visibility

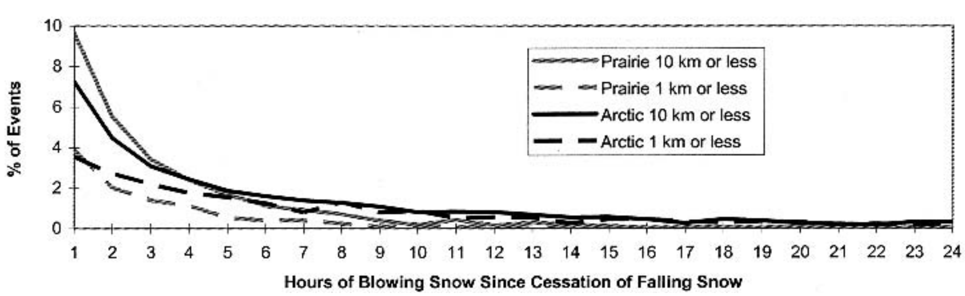

FIG. 5. Most instances of blowing snow with precipitating snow end when the falling snow terminates. The percentage of blowing snow events that outlast the falling snow diminishes with time since the end of the snow.

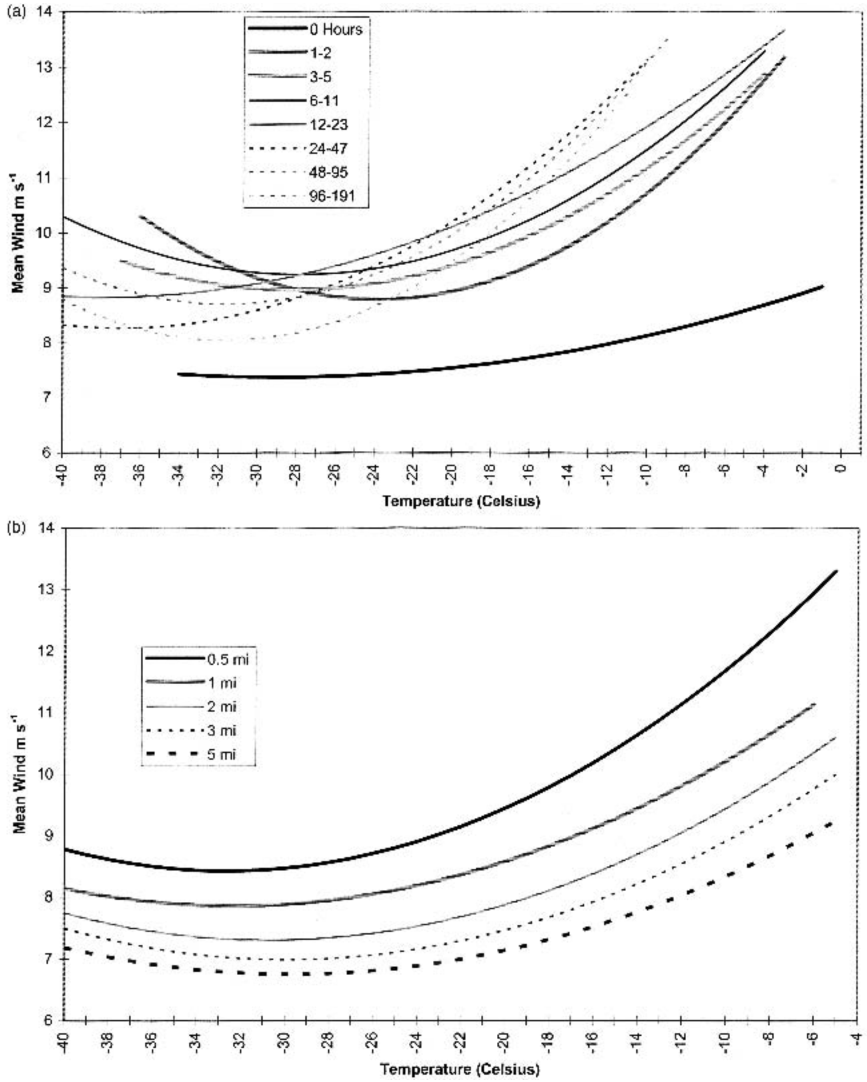

FIG. 6. (a) 5% CRED for various snowpack ages for the Arctic sites at a target visibility ≤ 1 km and using the current air temperature; (b) 5% CRED for various target visibilities in statute miles for all ground blowing snow cases for all observation sites using the current air temperature. The target visibilities include all occurrences equal or less than the stated threshold.

less than 1 km in blowing snow at each temperature for various snowpack ages. Figure 7b has the same distribution, but presented as a proportion of occurrences of temperatures at each snow age. In other words, Fig. 7b represents the number of significant blowing snow reports at a given temperature and snow age divided by the total number of reports of that same temperature and snow age. All hourly reports that occurred after melting conditions or after liquid precipitation were discarded. The result is the number of hits in a given set of circumstances normalized by the number of times those circumstances arise. The small number of cases of blowing snow with very old snowpacks leads to some scatter in the plots and is not shown. Blowing snow with concurrent falling snow does not show a strong dependency on temperature. These normalized frequency distributions of ground blowing snow peaks at an air temperature near minus 34°C regardless of the age of the snowpack even though the minima in the threshold wind are at milder temperatures for young snowpacks. These charts also indicate that at a given temperature, the likelihood of ground blowing snow is largely independent of the age of the snowpack.

d. Visibility distribution

One technique of forecasting visibility might begin with a method of predicting any snow movement using

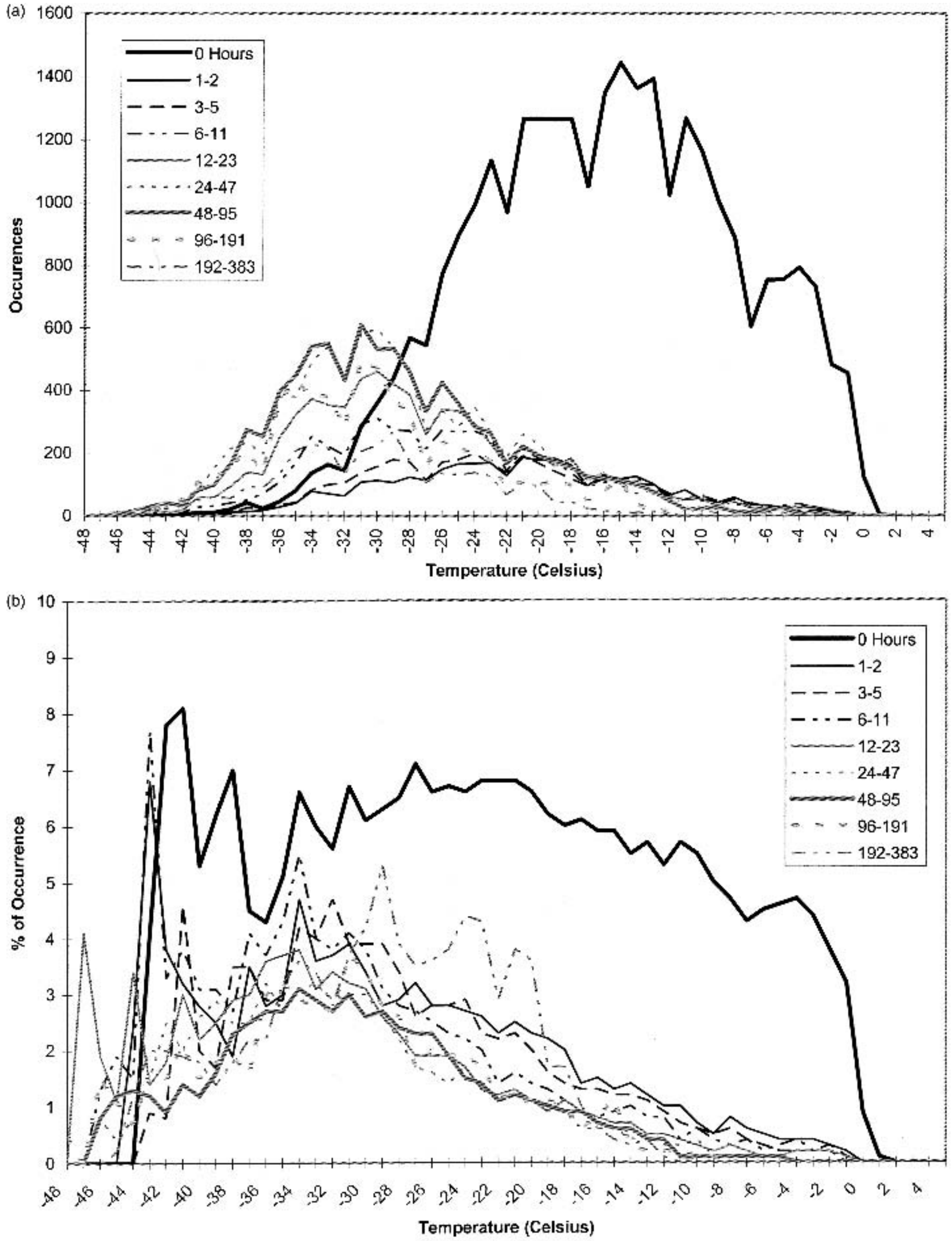

FIG. 7. (a). Number of occurrences of significant blowing snow (target visibility ≤ 1km) for all observation sites plotted by current air temperature and snow age; (b) blowing snow occurrences giving visibilities of 1 km or less at all stations as a proportion of the number of instances of these temperatures, sorted by snow age. All data that occurred after melt and freeze, or after liquid precipitation, were omitted.

a critical wind speed (Li and Pomeroy 1997b) and then applying a visibility distribution in blowing snow by wind speed in excess of this threshold (Fig. 8). Instances of blowing snow are rare with wind less than 5 m s^{-1} and very few of these are significant. Even at the 5% CRED critical speed, a minority of blowing snow cases has low visibilities. The distribution of visibilities varies with temperature (Figs. 8a–d). Colder temperatures favor a higher proportion of low visibilities at marginal wind speeds. The same trend was observed for older snowpacks. Not only is blowing snow more likely at higher wind speeds, a greater proportion of these events have significant visibility reduction. The specified visibility approach (Fig. 6a) where the critical wind speed is determined for set visibility restrictions simplifies the forecast process by requiring one nomogram

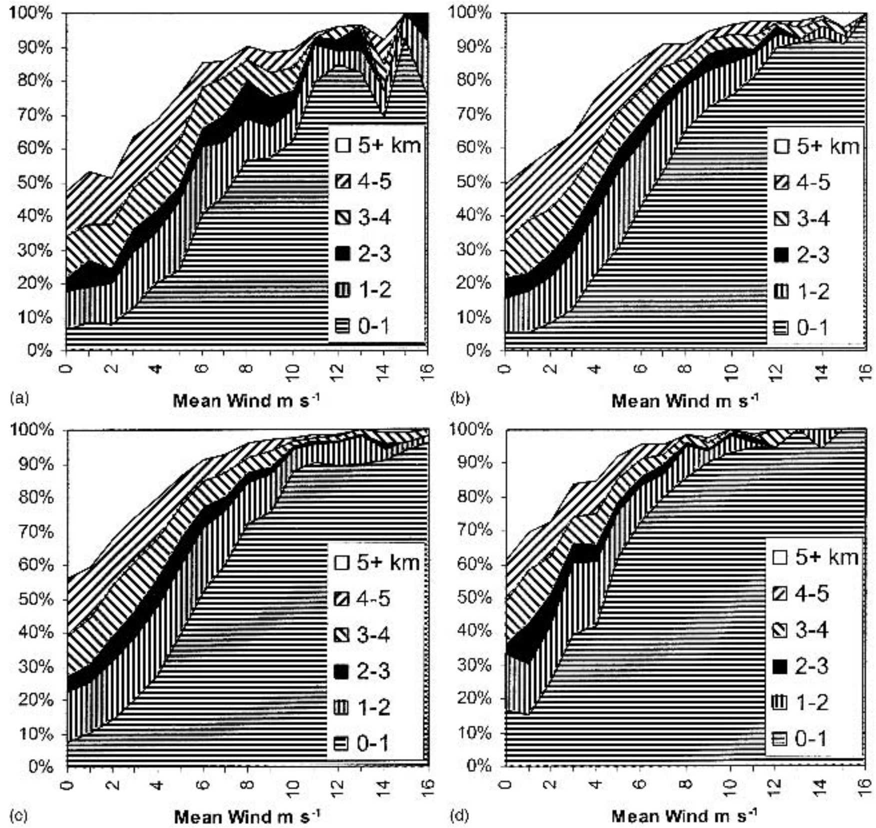

FIG. 8. Distribution of visibilities in reported ground blowing snow for all observation sites. The wind scale is speed in excess of the 5% CRED threshold for the current air temperature and appropriate age of the snowpack: (a) temperature 0 to −10°C, 4039 events; (b) −10 to −20°C, 12450 events; (c) −20 to −30°C, 16644 events; (d) −30 to −40°C, 4650 events.

instead of two. A suggested forecast process is provided in section 4.

e. *Evaluating wind thresholds for specified visibilities*

The 5% CRED critical wind was objectively evaluated as a potential forecast tool by testing it as a discriminator between cases where blowing snow with visibilities less than 1 km would or would not be expected. Observations with actual wind speeds above the 5% CRED critical wind would constitute a positive "forecast" of significant blowing snow that could then be verified against the reported weather. Various 5% CRED critical winds were derived using the data manipulation criteria listed in section 2b. The value of these criteria could then be assessed by their critical winds ability to distinguish cases of significant blowing snow.

The probability of detection (POD), false alarm ratio (FAR), and critical success index (CSI) were calculated for various specified visibilities, wind character, temperatures, and datasets:

$$\mathrm{POD} = x/(x + y), \tag{6a}$$

$$\mathrm{FAR} = z/(x + z), \tag{6b}$$

$$\mathrm{CSI} = x/(x + y + z), \tag{6c}$$

where x is a hit, or an occurrence with an actual wind speed higher than the 5% CRED threshold, and a concurrent visibility reduction due to blowing snow. Using the same criteria, y is a miss, and z is a false alarm. A higher CSI indicates that one method is a better discriminator of conditions that produce blowing snow. All tests shown here are for a visibility threshold of 1 km or less.

Tables 3a and 3b shows that the 5% CRED critical wind is a poorer discriminator of blowing snow events in cases with concurrent falling snow (CSI of 34.49%) than for those without (55.65%). Light falling snow on its own can have a visibility restriction close to 1 km. It would be very difficult to isolate the visibility restriction component due solely to the blowing snow. Blowing snow with falling snow does not have a strong temperature dependency, and so the 5% CRED critical wind is only marginally better than using a single wind speed threshold of 7.6 m s^{-1} for the whole temperature range.

TABLE 3a. Blowing snow with visibility ≤ 1 km and concurrent falling snow.

Threshold	Arctic vs Prairie datasets	Wind	Temperature	POD	FAR	CSI
Fixed speed (7.6 m s^{-1})	Combined	Mean	Independent	95.68	65.12	34.34
Li and Pomeroy (1997)	Combined	Mean	Current	95.80	65.86	33.64
5% CRED	Combined	Mean	Current	95.54	64.54	34.49
5% CRED	Separate	Mean	Current	95.54	65.06	34.38

TABLE 3b. Blowing snow with visibility ≤ 1 km but without concurrent falling snow.

Threshold	Arctic vs Prairie datasets	Snow age	Wind	Temperature	POD	FAR	CSI
Fixed speed (9.2 m s^{-1})	Combined	No	Mean	Independent	95.54	54.93	44.14
Li and Pomeroy (1997)	Combined	Yes	Mean	Current	95.30	48.66	50.07
5% CRED	Combined	No	Mean	Current	95.59	43.46	55.11
5% CRED	Combined	No	Mean	Maximum	95.51	42.82	55.68
5% CRED	Separate	No	Mean	Current	95.54	42.76	55.75
5% CRED	Separate	No	Mean	Maximum	95.59	42.49	56.03
5% CRED	Combined	Yes	Mean	Current	95.39	42.82	55.65
5% CRED	Combined	Yes	Mean	Maximum	95.25	41.17	57.15
5% CRED	Separate	Yes	Mean	Current	95.57	43.65	54.91
5% CRED	Separate	Yes	Mean	Maximum	95.57	42.78	55.74

TABLE 3c. Blowing snow with visibility ≤ 1 km but without concurrent falling snow.

Threshold	Arctic vs Prairie datasets	Snow age	Wind	Temperature	POD	FAR	CSI
5% CRED	Combined	No	Mean	Current	95.59	35.83	62.33
5% CRED	Combined	Yes	Mean	Current	95.51	38.57	59.70
5% CRED	Combined	Yes	Mean	Maximum	95.57	35.10	63.00
5% CRED	Combined	No	w/Gust	Current	95.65	33.61	64.45
5% CRED	Combined	Yes	w/Gust	Current	95.57	31.81	66.10
5% CRED	Combined	Yes	w/Gust	Maximum	95.53	33.19	64.79

However, using a temperature independent speed of 9.2 m s^{-1} for ground blowing snow has a CSI of 44.14%, which is much poorer than using the 5% CRED critical wind (55.65%).

Generally, using thresholds calculated for arctic and Prairie province groups separately shows a small improvement over using one threshold equation derived from the two groups combined (Table 3b). There were not enough cases of ground blowing snow in the Prairie provinces in the dataset with both mean wind and gusts to justify separate statistics. Using separate thresholds based on snow age is beneficial as is using the maximum temperature since the last snowfall (Table 3b, c). One would expect these two effects to be more important with older snowpacks. However, events with aged snow are fewer in number than those with freshly fallen snow. Therefore improving the discrimination of old snow events would not be expected to make great improvements in the overall CSI. Incorporating gust information makes a more significant improvement over just using the mean wind (Table 3c) as wind gusts will affect any snow age group. The CSI with gusts is 66.10% compared to 63.00% without.

4. Summary and conclusions

This paper has examined the occurrence of significant blowing snow events on the Canadian arctic and the Prairie provinces derived from historical hourly weather observations at 32 locations. Various descriptive statistics display some blowing snow characteristics. A critical success index of 66% can be achieved in discriminating blowing snow occurrences with certain specified visibilities using wind speed thresholds derived from this dataset. The highest CSI resulted when incorporating the most input data. This includes using information of wind gust, snow age, and highest air temperature since the last snowfall. Knowledge of the frequency and circumstances of past blowing snow occurrences at each station was also beneficial.

Developing the wind speed thresholds based on specified visibility restrictions proved to be the key in the performance of this technique of distinguishing conditions that are likely to generate blowing snow. Not only does the likelihood of blowing snow increase with wind speed, an increasing proportion of these events produce low visibilities. The coupling of these two trends leads to a sharper division between conditions that give high-impact blowing snow from all other cases. While blowing snow remains a chaotic process, forecast success is more likely if one focuses the objective to be predicting events giving very restricted visibilities. It is also these events that have the highest impact on transportation and public safety.

The wind speed thresholds found in this study could be employed as a method of forecasting future events. Although this is a purely empirical technique, it can be useful to the forecaster as an objective first guess of significant blowing snow events. A suggested process is as follows.

1) Forecast a wind speed and direction, and air temperature. Blowing snow prediction requires a precise and accurate wind forecast. The forecaster must account for the effects of local topography on wind speed and direction. A standard wind rose may be useful in this task.
2) Examine a blowing snow rose for the site in question, if applicable. These diagrams are useful for point forecasts but may not apply to nearby areas if the topography at the observation site is not representative of the surrounding area.
3) Check and note the snowpack history, if applicable. Do not forecast ground blowing snow if the snowpack has undergone melting, or has been exposed to liquid precipitation. Be aware that blowing snow may advect in from a distant location.
4) Use the appropriate nomogram to find the CRED. The nomogram selection would be based on the specified visibility, snow age, day versus night, current versus maximum temperature, and mean wind versus a combination of mean wind and gusts. For example, if one were expecting a wind of 60 km h^{-1} at $-10°C$, Fig. 3 would suggest a CRED around 80%. The forecaster would know that while blowing snow will likely occur, it is not necessarily guaranteed to do so. The forecast of wind and temperature will include some amount of uncertainty. Therefore, one should find CRED for a range of these forecast parameters. The spread of the extracted CRED will be an indicator of the confidence the forecaster should have in this process. In the example above, an error range of just 1°C and 10 km h^{-1} could produce a CRED as low as 30% or as high as 95%. On the other hand, if the temperature was expected to be -30 instead of $-10°C$, the CRED exceeds 95% over a similar range of uncertainty in the forecast inputs.
5) Knowledge of the local terrain, vegetation, fetch, climatology, surface temperature, depth of snow on the ground, etc., may be used to subjectively adjust the forecast. The aerial occurrence of blowing snow can vary greatly due to these factors. The effects of these elements are described in Li and Pomeroy (1997b).

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