JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. D18, PAGES 21,955–21,964, SEPTEMBER 27, 1997

Probability of occurrence of blowing snow

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Abstract. Blowing snow (snow transport) affects snow cover distribution and snowmelt runoff patterns in cold, wind-swept regions. This paper uses a statistical method to examine the occurrence of blowing snow and the meteorological conditions recorded for 16 stations on the prairies of western Canada over six winters. The results show that the occurrence probability is highly related to wind speed, air temperature and snow age. For the same air temperature and snow age, the occurrence probability increases with increasing wind speed. The probability distribution of occurrence with respect to wind speed approximates a cumulative normal probability distribution, depending on the mean and variance of wind speed: the location and scale parameters of the normal distribution. It was found that these two statistical parameters essentially indicate snow resistance and sensitivity to wind transport. Analysis of the probability distributions for the occurrence of blowing snow for different classes of air temperature and snow age reveals that the mean wind speed of the normal distribution generally increases with increasing air temperature and snow age, and the variance of wind speed increases with increasing air temperature. This leads to the development of a model which first estimates the two parameters of the normal distribution using air temperature and snow age, and then estimates the probability of the occurrence of blowing snow using wind speed and the two parameters with the cumulative normal probability function. Comparison of hours of occurrence of blowing snow and of fluxes of snow transport and sublimation estimated using the model to those determined using observations of occurrence of blowing snow shows good agreement. The results of this study can be used to estimate the frequency of blowing snow events using standard meteorological data, to determine the snow transport and snow sublimation fluxes, and to examine the effect of meteorological conditions on blowing snow processes.

Introduction

Blowing snow (snow transport) causes snow cover redistribution and water loss by blowing snow sublimation. This is an important hydrological process in the world's cold regions [*Pomeroy and Gray*, 1995]. A number of numerical models have been developed for estimating snow transport fluxes by wind [e.g., *Kind*, 1976; *Dyunin and Kotlyakov*, 1980; *Schmidt*, 1986; *Pomeroy et al.*, 1993]. One of the most critical inputs to these models is the time period of occurrence of blowing snow. *Li and Pomeroy* [1997] show that wind transport of dry snow can be initiated at wind speeds ranging from 4 to 11 m/s, where the wind speed is that found at the 10 m height. *Schmidt* [1980] reports that warm snow and aging snow require a higher wind speed to initiate transport than cold snow and fresh snow, respectively. In concurrence, *Li and Pomeroy* [1997] found that transport thresholds increased with increasing air temperature and snow age. However, there is no standard method for determining meteorological conditions under which blowing snow occurs.

Blowing snow takes place when the wind shear stress exceeds snow particle resistance. Whether blowing snow occurs or not depends largely on a combination of wind speed, snow particle cohesion and bonding resistance. The driving and resistant forces in field conditions are so complicated that it is extremely difficult to determine occurrence of blowing snow on a deterministic, physical basis. However, wind speed can provide a simple representation of the "driving force" by simple application of Prandtl-von Kármán boundary layer theory and, similarly, air temperature and time, since the snow deposition can represent the "resistant force" through their effect on snow particle cohesion and bonding [*Hobbs and Mason*, 1964; *Hosler et al.*, 1957; *Ôura et al.*, 1967; *Schmidt*, 1980].

Wind driving force and snow resistance are also influenced by other factors such as topography, vegetation, and snow crystal form. Wind speed, air temperature and snow age alone are insufficient for exactly determining the occurrence of blowing snow. For instance, the hourly, 10-m wind speed is an average value and only an indicator of wind driving force. In addition, snow resistance is affected by precipitation processes. The 10-m wind speed, 2-m air temperature and snow age do not directly and consistently reflect these differences. However, these three parameters are hypothesized to provide sufficient information to determine the occurrence of blowing snow on a probabilistic basis. This study will therefore take a statistical approach to determine the probability of the occurrence of blowing snow from these readily measured parameters. The results should help to predict blowing snow events and to estimate snow transport and sublimation fluxes on an operational basis and in atmospheric and hydrological models.

Paper number 97JD01522
0148-0227/97/97JD-01522$09.00

Physical Basis for Occurrence of Blowing Snow

The resultant force of wind shear stress, snow cohesion, bonding and frictional resistance primarily determines occurrence and persistence of blowing snow. These forces are much more important than, e.g., particle weight [*Schmidt*, 1980]. Wind shear stress τ, acting as a driving force for blowing snow, is directly related to wind speed as follows:

$$\tau = \rho \left[\frac{k U_z}{\ln(z/z_o)} \right]^2 \qquad (1)$$

where ρ is air density, k is von Kármán's constant (0.4), U_z is wind speed (m/s) at the height z (meters), and z_o (meters) is surface roughness length. This equation shows the connection between wind speed and the driving force for blowing snow.

Snow cohesive resistance, or viscous force, is associated with snow wetness. Air temperatures at or above 0°C often result in snow surface temperatures at the melting point and hence in wet snow on the surface. Cohesive resistance increases dramatically as snow becomes wet. Several authors have demonstrated the existence of a liquid water film on ice surfaces even at ambient air temperatures below 0°C [*Nakaya and Matsumoto*, 1954; *Jellinek*, 1957; *Hosler et al.*, 1957; *Ôura et al.*, 1967; *Conklin and Bales*, 1993]. Experiments on snow show that cohesion between snow particles increases exponentially with increasing temperature and particle size. *Schmidt* [1980] used the following empirical expression to describe the effect of snow temperature T (°C) on cohesion F (shown here in a ratiometric dimensionless form) soon after contact:

$$\frac{F}{F_{-15}} = 8\, e^{0.141T} \qquad (2)$$

where F_{-15} is the cohesion at -15°C. This expression indicates that cohesion of snow increases exponentially with temperature such that for particles at 0°C it is 8 times that at -15°C, presumably as the liquid layer on the surface of snow particles becomes substantially thicker at 0°C.

Snow particle bonding resistance to transport is associated with the snow aging processes. Snow particle bonding tends to increase gradually from day to day as a result of small mass and energy fluxes. One important process that leads to the gradual increase is metamorphism, which usually tends to increase the bond strength of surface snow layer. Metamorphism can occur under a variety of temperature gradients with the snowpack. Water vapor, controlled by the vapor pressure, diffuses from the warmer to the colder part of snowpack, where the saturation vapor pressure is lower, condensation occurs, and crystals grow. This process occurs due to vertical gradients in snowpack temperature and is termed temperature gradient metamorphism [*Sommerfeld and LaChapelle*, 1970; *Colbeck*, 1987]. Snow metamorphism also occurs when the temperature is uniform with snowpack depth or gradients are very small [*Sommerfeld and LaChapelle*, 1970]. The vapor pressure varies with the shape of ice crystals; vapor pressure decreases from a convex surface, though a plane surface, to a concave surface. At this microscopic scale where temperature is relatively uniform, vapor moves from convex surfaces to concave surface. As this process occurs under conditions of uniform temperature, it is known as equitemperature metamorphism. Both metamorphism processes increase snow particle bonding resistance to wind transport gradually over time. According to laboratory work, *Hobbs* [1974] reports that the bond growth of ice spheres is directly related to time t and temperature T as

$$\left(\frac{x}{R}\right)^5 = \frac{B(T)t}{R^3} \qquad (3)$$

where x is the radius of the neck which bonds two similar ice spheres on the surface, R is the radius of the ice spheres, and $B(T)$ is a function of temperature described in detail by *Hobbs* [1974]. *Keeler* [1969] demonstrated that x/R increased from 0.02 for natural dry snow 2 days old to 0.25 by day 47 after deposition.

Li and Pomeroy [1997] showed that frictional resistance due to kinetic friction and elasticity may influence the transport threshold for blowing snow at low temperatures. Kinetic friction is a resistance to sliding that increases in a nonlinear manner with decreasing temperature. Elasticity increases 30% as the snow temperature drops from -1 to -40°C [*Mellor*, 1975]. As elasticity increases, the particle impact force necessary to break particle bonds increases. As a result, threshold wind speeds for transport at temperatures below approximately -27°C were observed to be higher than those for temperatures immediately above this temperature. This effect is due to the increase in frictional resistance at low temperatures which may restrict the occurrence of blowing snow.

Other processes such as wind packing and age hardening are also responsible for the growth of ice bonding strength due to time densification of snow. *Gray et al.* [1970] found that snow density increased from 45 to 230 kg m^{-3} within 24 hours by wind packing. *Yong and Metaxas* [1985] reported that at a relatively constant temperature of -13°C, the density of the natural fresh snow (initially about 100 kg m^{-3}) aged for 30 and 50 days increased to 300 and 400 kg m^{-3}, respectively.

Snow particle bonding and cohesion can increase drastically due to the freeze-thaw process. If the air temperature rises to 0°C or above, bonds weaken but cohesion increases substantially. If the air temperature falls from above to below the freezing point, or wet precipitation (i.e., rain, freezing rain, or freezing drizzle) is received, snow will become icy. Wet/icy snow is extremely resistant to wind transport as a result of increase in the cohesion or bonding strength.

Accurate determination of the wind driving and snow resistance forces is formidable under field conditions due to turbulent wind, the complex of snow properties (e.g., size, shape), competing and counterbalancing component forces, and varying meteorological conditions over time. However, statistically representing these forces with the meteorological parameters wind speed, air temperature, and time since snowfall permits the examination of occurrence of blowing snow with meteorological data.

Meteorological Observations

The Atmospheric Environment Service (AES) of Environment Canada makes visual observations of the hourly occurrence of "blowing snow" and "drifting snow" at its manned primary climatological stations ("blowing snow" recorded in the AES digital archives and "drifting snow" recorded by hand in the remarks column of the daily synoptic data sheets). Blowing snow is defined by AES as snow lifted by the wind such that it obscures visible range at "eye level" to less than 9.7 km. Drifting snow is a visual observation of snow moving along the ground and is relatively more subjective. The distinction by AES between blowing and drifting snow is arbitrary. In this study, both blowing snow and drifting snow from the AES archives will be referred to as blowing snow. Confidence in the visual observations of occurrence of blowing snow is high because the saltating layer of blowing snow near the ground sustains mean mass concentrations from 0.4 to 0.9 kg m^{-3} for mean wind speeds greater than 0.25 m/s above the transport threshold [*Pomeroy and Gray*, 1990]. The average visual range through this layer of blowing snow near the ground is less than 0.87

Figure 1. Location of the meteorological stations in the Prairie Provinces of western Canada.

m as calculated using Mie scattering theory [*Pomeroy and Male*, 1988], which corresponds to a ratiometric transmittance of 0.64 for 600-nm wavelength light through a 10-cm vertical slice of saltating snow. Hence the light extinction effects of saltating snow are easily and immediately discernible under daylight or artificial lighting conditions. The intermittent and high variable nature of saltating snow transport near the threshold condition means that visibility is temporarily diminished below this level, which improves the prospect of visible identification beyond that estimated using mean values. During most blowing snow events, the problem of meteorological observers is not in identifying the blowing snow but in being able to observe anything else. Hence the observational record of blowing snow is considered quite good.

AES hourly meteorological observations from 16 stations in the Canadian Prairies were used to examine the probability of occurrence of blowing snow in relation to wind speed, instantaneous air temperature, and occurrence of precipitation from November 1970 to April 1976. Microfilms of daily synoptic sheets ("drifting snow" occurrence) are available for this time period and were digitized to provide a complete database of occurrence of blowing snow. The stations, in the provinces of Alberta, Saskatchewan, and Manitoba (Figure 1 and Table 1), represent regional climates from cool and subhumid, with lower wind speeds and few midwinter melts in the northeast, to warmer and semiarid with higher wind speeds, frequent midwinter melts, and Chinooks (Foehn-like winds) in the southwest. This is the only known digital data set of observations of occurrence of both "blowing" and "drifting" snow.

AES meteorological data provide the time over which blowing

Table 1. Meteorological Stations Used to Examine the Probability of Occurrence of Blowing Snow

Station	Province	Anemometer Height, m						Temperature[a], °C	Snowfall[b], mm
		1970-1971	1971-1972	1972-1973	1973-1974	1974-1975	1975-1976		
Calgary	Alberta	20.4	20.4	20.4	18.3	18.3	18.3	-4.7	122
Coronation	Alberta	13.4	13.4	13.4	13.4	13.4	13.4	-8.4	169
Medicine Hat	Alberta	10	10	10	10	10	10	-4.4	113
Peace River	Alberta	10	10	10	10	10	10	-10.3	155
Dauphin	Manitoba	10	10	10	10	10	10	-10	141
Portage La Prairie	Manitoba	9.1	9.1	9.1	9.1	10	10	-8.9	143
Winnipeg	Manitoba	10	10	10	10	10	10	-9.7	106
Broadview	Saskatchewan	10	10	10	10	10	10	-9.3	123
Estevan	Saskatchewan	10	10	10	10	10	10	-7	107
Moose Jaw	Saskatchewan	10	10	10	10	10	10	-7.1	127
North Battleford	Saskatchewan	11	11	11	11-14	14-10	10	-9.8	111
Prince Albert	Saskatchewan	10	10	10	10	10	10	-11.6	103
Regina	Saskatchewan	10	10	10	10	10	10	-8.9	113
Swift Current	Saskatchewan	10	10	10	10	10	10	-6.7	132
Wynyard	Saskatchewan	10	10	10	10	10	10	-9.9	126
Yorkton	Saskatchewan	10	10	10	10	10	10	-10.6	125

[a] Average of hourly values from November 1 to April 30, 1970-1976.
[b] Total water equivalent from November 1 to April 30, 1970-1976.

snow occurs, wind speed, temperature, the occurrence of precipitation, and the existence of snow on the ground on an hourly scale. AES air temperature is the dry bulb temperature measured at 2-m height, and wind speed is measured by a cup anemometer. Most of the anemometers at the 16 locations used were mounted at 10 m above the ground in a flat, open, grassy exposure such as at an airport, but some were not. Stability corrections are insignificant in the lower boundary layer during blowing snow, permitting the use of a standard log-linear wind speed profile for conditions where saltation does not induce an additional surface roughness [*Schmidt*, 1982; *Pomeroy and Gray*, 1990]. Using the following method, wind speeds other than those measured 10 m above the ground were converted to the 10-m wind speed:

$$U_z = \frac{u*}{k} \ln(\frac{z}{z_o}) \quad (4)$$

where U_z is wind speed (m/s) at height z (meters), u_* is friction velocity (m/s), k is von Kármán's constant (0.4), and z_o (meters) is surface roughness length, which is 0.5-10.0 x 10^{-4} (meters) [*Oke*, 1978]. For this conversion, z_o was assumed as 0.5 x 10^{-4} (meters). Knowing U_z, z, k and z_o, u_* was found by (4). Then given u_*, z = 10 m, k, and z_o, U_z was converted to U_{10}, the 10-m wind speed (m/s). The correction could not be made for the differential exposure of anemometers due to limited information, though in general, this is not a significant problem on the Canadian prairies, where AES stations are located in open environments with grass surfaces.

Frequency of Occurrence of Blowing Snow

The frequency of occurrence of blowing snow is presumed to be different for dry snow covers than for wet/icy snow covers. Dry snow is defined here as snow which has neither received air temperatures ≥0°C nor wet precipitation since the last snowfall. Wet/icy snow is defined as snow which has either received melting temperatures of 0°C or above or wet precipitation since the last snowfall. If the air temperature drops below 0°C, the wet snow surface will become icy, and hence the joint classification. The

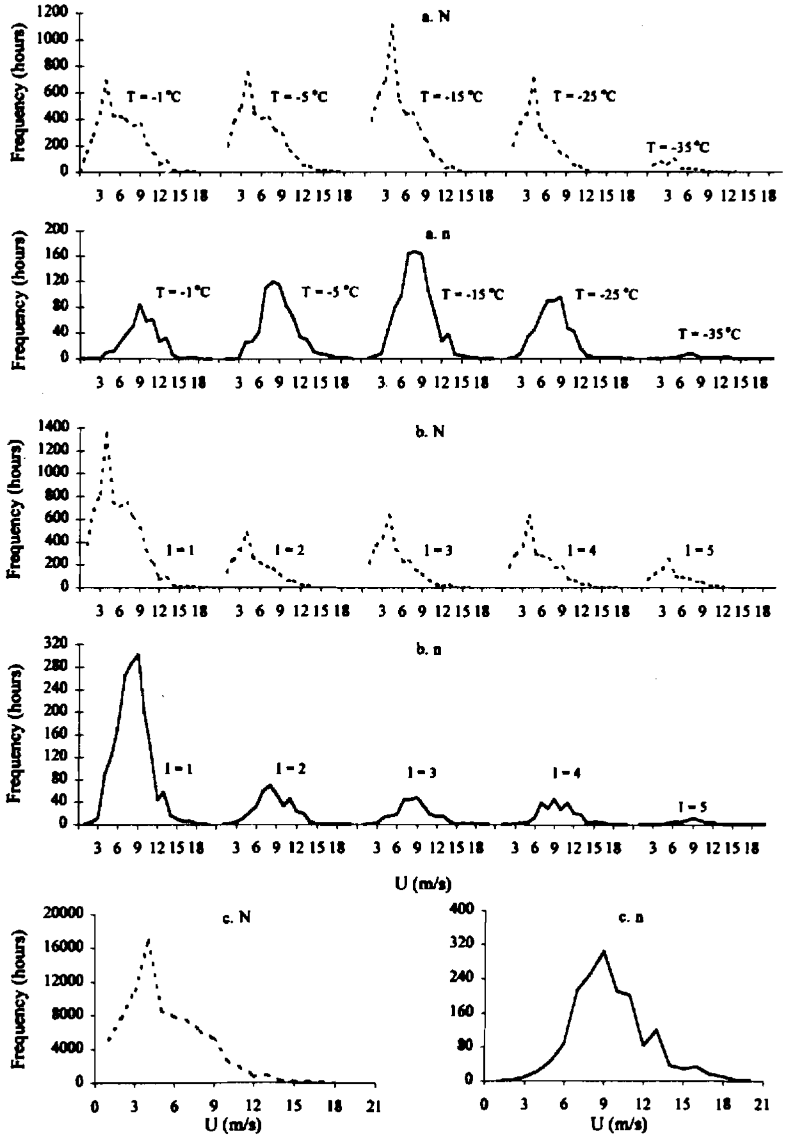

Figure 2. Frequency of wind speeds, with blowing snow (*n*) and with snow on the ground (*N*), for the Canadian Prairie meteorological stations, 1970-1976 snow years. (a) Dry snow conditions by ambient air temperature. (b) Dry snow conditions by snow age index. (c) Wet/icy snow conditions.

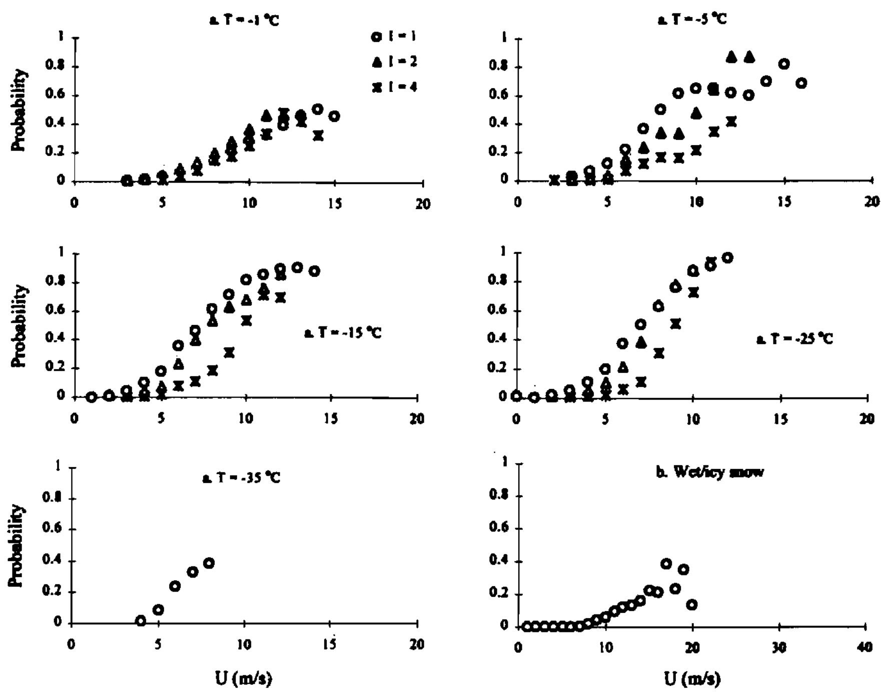

Figure 3. Probability of occurrence of blowing snow with different temperatures and snow ages (3, 7, and 55 hours). (a) Dry snow conditions. (b) Wet/icy snow conditions.

frequency of occurrence of dry blowing snow was calculated for individual groups of wind speed, air temperature, and snow age, each as an index to wind shear stress (1), snow cohesion, and bonding resistance (2) and (3), respectively. To obtain a sufficient sample size of the individual groups, an arbitrary snow age index I was defined as

$$I = \ln m \tag{5}$$

where m (hours) is the time since snow deposition. For calculation purposes, m was assigned to 1 for fresh snow. For the data set, I ranges from 1 to 5, each representing snow ages from 1-2.7, 2.7-7.4, 7.4-20.1, 20.1-54.6, and 54.6-148.4 hours. Equation (6) was used to calculate the frequency of occurrence of blowing snow, $f(U, T, I)$:

$$f(U, T, I) = \frac{n}{N} \tag{6}$$

where U (m/s) is wind speed at 10-m height, T (°C) is ambient air temperature at 2-m height above the ground, n is the number of occurrences of blowing snow events under the specific condition (U_{10}, T, I), and N is the number of occurrences of that specific condition with snow recorded on the ground. The intervals for U, T, and I are all equal to 1 for the individual groups. Figures 2a and 2b show the magnitude of n and N with wind speed for representative classes of temperature and dry snow age. Equation (6) was also used to calculate the frequency of occurrence of wet/icy blowing snow but with only one variable, wind speed. The other two variables, air temperature and snow age, were dropped because wet/icy snow by definition receives warm air temperatures and hence has very high resistance to wind transport, regardless of snow age. Figure 2c shows the magnitude of n and N with wind for wet/icy snow. Since the sample size N is large for most groups of the wind speed, air temperature, and snow age index, the relative frequency of occurrence of blowing snow, n/N, is considered equivalent to the probability of occurrence of blowing snow.

The probability of occurrence of blowing snow is shown in Figure 3 for five representative dry snow conditions and one joint wet/icy snow condition using data from 16 stations on the prairies of western Canada over six winters. In spite of some scatter where the sample size is small, a nonlinear change in probability with wind speed is evident. In general, the probability increases with increasing wind speed (at the same air temperature and snow age index), with decreasing air temperature (at the same wind speed and snow age index), and with decreasing snow age index (at the same wind speed and air temperature). These three features of Figure 3 can be readily explained by (1), (2), and (3), respectively, as a high wind results in a high wind driving force, a low temperature in a low cohesive resistance, and a fresh snow in a low bonding resistance. It is clearly indicated that wind speed, air temperature, and time since snow deposition may be used to determine the probability of occurrence of blowing snow.

Model of Occurrence of Blowing Snow

The probability distribution of occurrence of blowing snow with respect to wind speed (Figure 3) resembles a cumulative normal probability distribution,

$$P(U_i, T, I) = \frac{1}{\delta\sqrt{2\pi}} \int_0^{U_i} e^{-\frac{(\bar{U} - U_i)^2}{2\delta^2}} dU \tag{7}$$

where U_i is current wind speed and $\bar{U}$ and δ^2 are the mean and the variance, respectively, of wind speed. The two parameters of the normal distribution are defined as

$$\bar{U} = \sum_{i=1}^{\infty} \frac{\Delta P(U_i, T, I)}{\Delta U} U_i \tag{8}$$

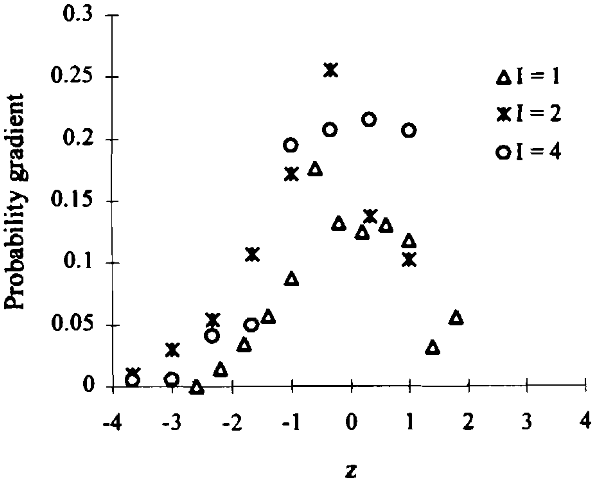

Figure 4. Typical probability gradient distribution of occurrence of blowing snow ($\Delta P/\Delta U_{10}$): temperature T = -25 °C, snow age index I = 1, 2, and 4 (3, 7, and 55 hours). Note the normalized wind speed (z statistic).

$$\delta^2 = \sum_{i=1}^{\infty} \frac{\Delta P(U_i, T, I)}{\Delta U} (U_i - \bar{U})^2 \qquad (9)$$

where $\Delta P(U_t, T, I)/\Delta U_{10}$ is the probability gradient with respect to wind speed and its distribution should approximate a normal distribution. Note that the probability of occurrence of blowing snow, $P(U_t, T, I)$ is inversely related to the mean of wind speed $\bar{U}$, as shown by (7).

The mean and the variance are commonly referred to as the location and scale parameters for the normal distribution. If $U_t = \bar{U}$, P = 0.5 according to (7). The mean wind speed gives the location where there is a 50% probability of occurrence of blowing snow (Figure 3) and where the normal distribution is centered. The mean wind speed in this case indexes the resistance of snow covers to wind erosion. The variance of wind speed controls the slope of the cumulative normal probability distribution curve, or the rate at which the probability of occurrence of blowing snow changes with changing wind speed (Figure 3) and the scale of the normal distribution. Note that the smaller the variance of wind speed; the higher the rate at which the probability of occurrence of blowing snow changes with changing wind speed around the mean wind speed (7). The variance of wind speed is in this sense a parameter indicating the sensitivity of snow covers to wind transport

The probability gradient distribution appears roughly symmetrical or normal in Figure 4, where the probability gradient is plotted versus normalized wind speed, z, [$z = (\bar{U}-U)/\delta$] for three typical cases from observations. This supports the choice of the cumulative normal probability distribution (7) to fit the probability distribution of occurrence of blowing snow. Using (7) to match the frequency of occurrence of blowing snow for dry snow, as observed by AES (Figure 3), the best fit mean and variance of wind speed were estimated by trial and error for the different conditions of temperature and snow age index. The mean and variance of wind speed were then related to air temperature T and snow age index I as follows:

$$\bar{U} = 0.365T + 0.00706T^2 + 0.9I + 11.2 \qquad (10)$$

$$\delta = 0.145T + 0.00196T^2 + 4.3 \qquad (11)$$

For warm temperatures (>-25°C), $\bar{U}$ increases with increasing temperature and increasing snow age, and δ increases with increasing temperature. As the probability of occurrence of blowing snow is inversely related to the mean of wind speed (7), (10) implies that for a given wind speed and the warm temperature range, the warmer

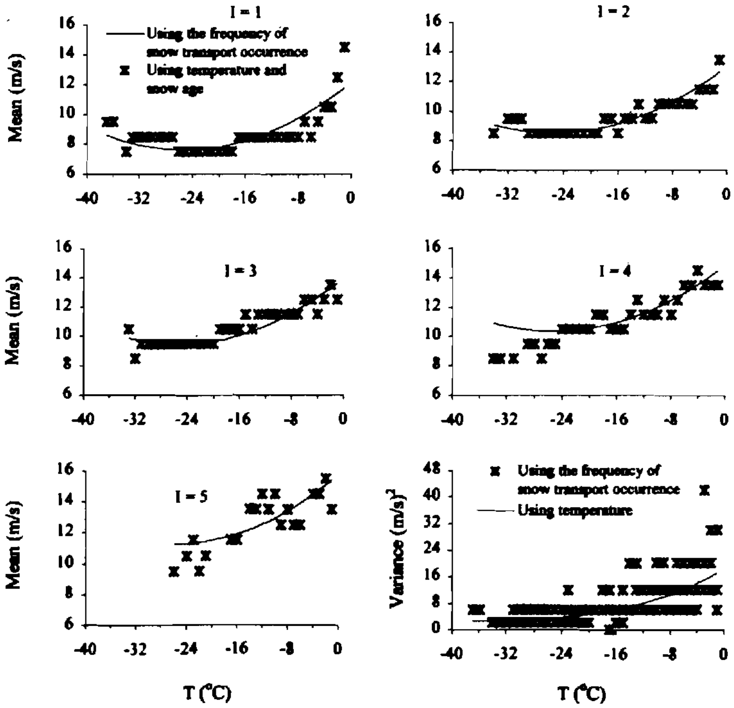

Figure 5. The mean and variance of wind speed from the normal probability distribution of occurrence of blowing snow, estimated using the frequency of occurrence of blowing snow observed by AES and by using ambient air temperature and snow age with (10) and (11) for the normal distribution of probability gradients.

the ambient air temperature and the older the snow age; the lower the probability of occurrence of blowing snow. This is because the warmer, older snow is more resistant to wind transport, as discussed earlier. At low temperatures (<-25°C) the probability of occurrence of blowing snow declines with declining temperature. The change of direction in the relationship is due to the prominence of frictional resistance forces at cold temperatures, which restrict the occurrence of blowing snow.

As the rate at which the probability of occurrence of blowing snow changes with changing wind speed around the mean is inversely proportional to the variance of wind speed (7), (11) indicates that for temperatures >-37°C, the warmer the ambient air temperature, the smaller the change in the probability of occurrence of blowing snow with a given change in wind speed. For example, if the wind speed increases from 5 to 10 m/s, the increase in probability of occurrence of blowing snow will be smaller at an air temperature of -5°C than of -25°C. This is because the cold snow is less resistant and hence more sensitive to shear forces applied by the wind. At very cold temperatures the variance begins to increase slightly, indicating a decreased sensitivity to shear force.

The mean and the variance of wind speed estimated by (10) and (11) are compared to those estimated directly from observations using (8) and (9) for the frequency of occurrence of dry blowing snow (Figure 5). The mean and the variance of wind speed could not be estimated directly using (8) and (9) for all cases because of a limited range of observational conditions. For instance, there are no observations to show the probability of occurrence of dry blowing snow for wind speeds above 15 m/s at temperatures of -1°C, and above 8 m/s at temperatures of -35°C. Comparing the mean and variance of wind speed between model estimates and estimates from observations provides a coefficient of determination (R^2) and standard error of estimate of 0.83 and 0.76 for (10) and of 0.59 and 0.50 for (11), respectively. As is clear from Figure 5 for low snow cover ages, the mean wind speed is high for extremes of warm and cold temperatures, showing the effect of cohesion at high temperatures and frictional resistance at low temperatures. For high ages a steady decline in mean wind speed with decreasing temperature is evident, though the smaller temperature range and smaller number of observations make this trend less clear. It is possible for well-bonded older snow covers that frictional resistance is small compared to average bond strength, though cohesion remains strong. Using the same method, the best fit mean and variance of wind speed were found as 21 and 49 m/s, respectively, for occurrence of wet/icy blowing snow.

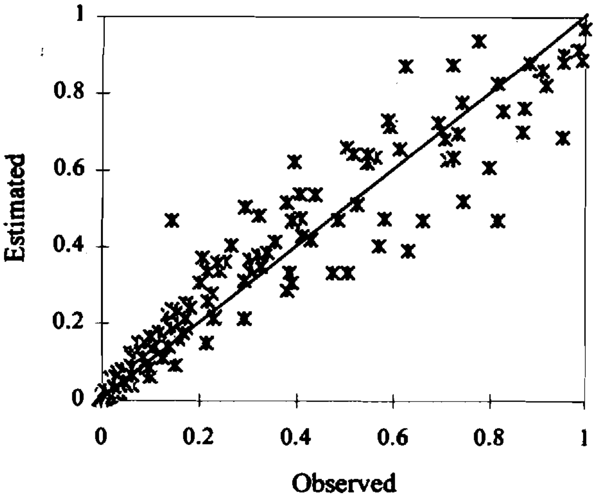

Figure 6. Probability of occurrence of blowing snow observed and estimated for dry and wet/icy snow conditions.

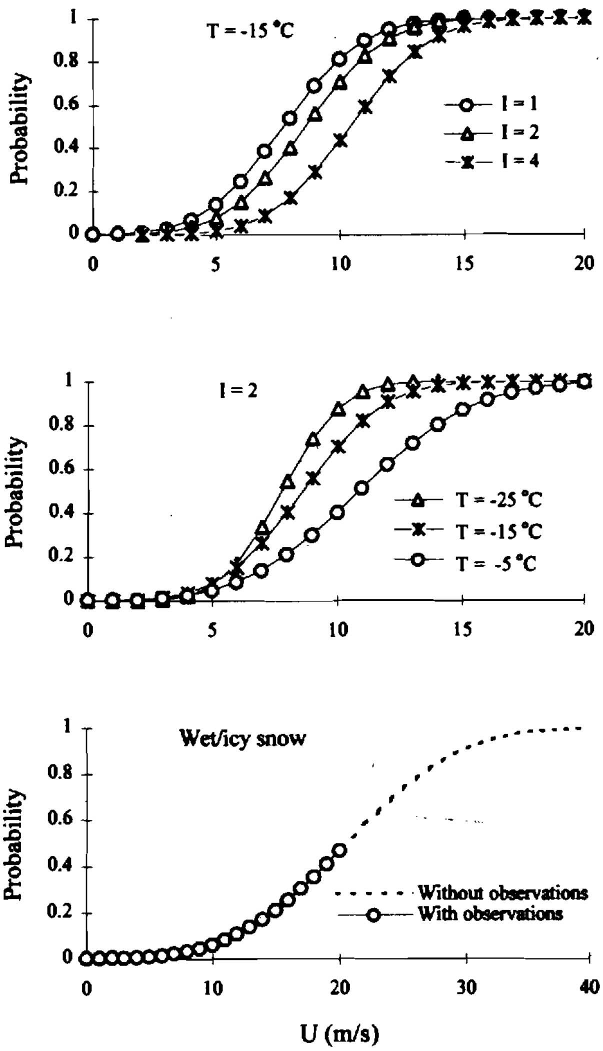

Figure 7. Variation of the probability of occurrence of blowing snow with air temperature, snow age (3, 7, and 55 hours), and icy/wet conditions.

The probability of occurrence of blowing snow was calculated using (7) with observed wind speed and the estimated mean and variance of wind speed using (10) and (11). A good agreement between the observed and estimated probability is shown in Figure 6 for both dry snow and wet/icy snow conditions. The coefficient of determination (R^2) and standard error of estimate for (7) are 0.92 and 0.091 for dry snow and 0.72 and 0.084 for wet/icy snow, respectively. This shows that the cumulative normal probability can be used to fit the probability of occurrence of blowing snow with an acceptable level of accuracy.

The probability of occurrence of blowing snow estimated using the normal probability distribution function is always >0 and ≤1. To show the variation of occurrence of blowing snow with air temperature, snow age and icy/wet conditions, the occurrence probability for three different conditions was calculated using (7) and plotted in Figure 7. The occurrence probability of dry blowing snow is always 100% when the wind increases to 20 m/s and becomes very low (but not zero) when the wind is below 3 m/s, regardless of air temperature and snow age. For wet/icy snow the probability of occurrence of blowing snow is only 50% with the wind at 20 m/s and did not reach 100% within the measured conditions. The observations show that if the wind speed is very low and the snow is dry, or the wind speed is moderate and the snow is wet or icy, then it is almost impossible for blowing snow to occur (Figure 3). However, the model shows a greater than zero probability for these conditions because of the curve fits used. Therefore (7) should be used with caution for these low wind speed or wet/icy snow conditions, and it is recommended that a zero probability be assigned for wind speeds less than 3 m/s. It should also be noted that as the data set from which this model is derived primarily exists for air temperatures greater than -35°C and wind speeds less than 20 m/s, the application of the preceding equations outside of these limits is not recommended without field verification.

Model Application

The probability model was incorporated into existing blowing snow models to estimate the annual frequency of occurrence of blowing snow and the fluxes of snow transport and sublimation. As an example of application, this model was run using AES hourly meteorological data (wind speed, temperature, the occurrence of precipitation and snow cover depth) to calculate the total hours of occurrence of blowing snow for Calgary, Alberta; Regina, Saskatchewan; and Portage La Prairie, Manitoba (Figure 1), 1973-1974 and 1974-1975 snow years. The first year was extraordinarily windy and snowy, while the second was more normal. Calgary, located in the west, is warm and windy with frequent Chinooks; Regina, in the middle, is snowy and windy; Portage La Prairie, in the east, is cold, snowy, and less windy (see Table 1). These three stations serve to represent the range of climate in the Canadian prairies. The model applications shown are compared to data selected from the more complete data set from which the model was derived; hence the tests are not independent. It was considered of primary importance to use all available observational data in developing the probabilistic model; hence there are no known hourly data with digitized drifting snow occurrence that can be used to verify the model that were not used in developing the model. The applications shown here should be viewed strictly as tests or demonstrations of the annual or shorter time period performance of the algorithms at various sites and not as verification of the algorithm development, which was indicated by statistics shown in the previous section.

The estimated annual frequency of occurrence of blowing snow is the yearly sum of the hourly probability of occurrence of blowing snow (multiplied by 1 hour). This estimated frequency is compared with the annual hours of blowing snow (our definition) observed by AES in Figure 8. For the three sites over the 2 years of application, the coefficient of determination (R^2) and standard error of estimate of the comparison are 0.95 and 64, respectively, indicating that the model provides an accurate estimation of the number of hours with blowing snow over a wide range of climatic and weather conditions. Interestingly, the location with both high snowfall and strong wind speeds (Regina) experienced a much higher frequency of blowing snow than the colder or warmer stations.

Using output from the probability model, a one-dimensional version of the Prairie Blowing Snow Model (PBSM) [*Pomeroy*, 1988; *Pomeroy et al.*, 1993; *Pomeroy and Gray*, 1995] was run to estimate snow transport and sublimation fluxes for the same locations and the same time periods given a fetch set to provide a boundary layer height of 15-20 m for flux calculations. The inputs to PBSM include the 10-m wind speed, air temperature, relative humidity, wind speed at which blowing snow ceases (i.e., cessation or dynamic threshold, which is about 80% of the initiation threshold [*Greeley and Iversen*, 1985]), fetch distance, and land use. PBSM outputs snow transport (saltation and suspension) and sublimation fluxes. Equation (12), developed by *Li and Pomeroy* [1997] from the same Canadian prairie data set, was used to estimate the average threshold wind speed for saltation flux calculation in the PBSM:

$$U_t = 9.43 + 0.18T + 0.0033T^2 \qquad (12)$$

where U_t (m/s) is the wind speed (10-m height) that initiates blowing snow (threshold wind speed), and T (°C) is the ambient air temperature at 2-m height. If the wind speed for a particular hour is lower than the estimated average threshold, there is still a chance for the probability of blowing snow to be greater than zero. As an

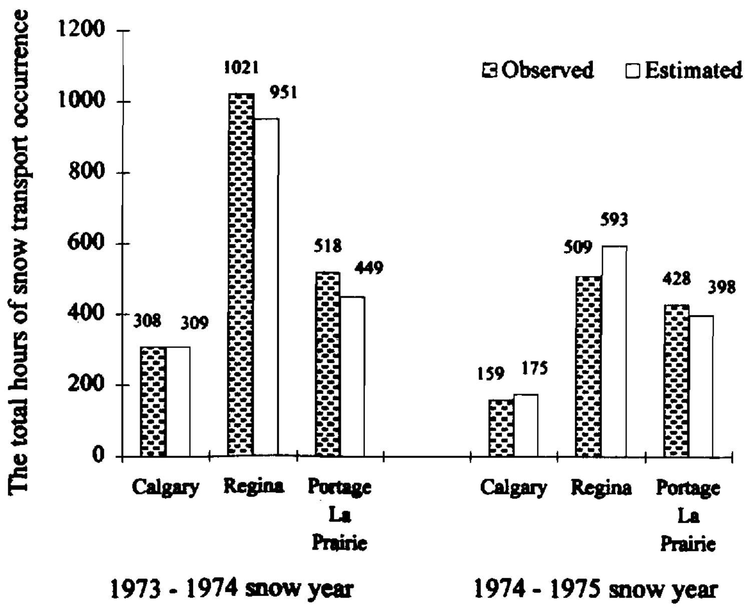

Figure 8. Frequency of occurrence of blowing snow observed and estimated for Calgary, Regina, and Portage La Prairie, Canada, 1973-1974 and 1974-1975 snow years.

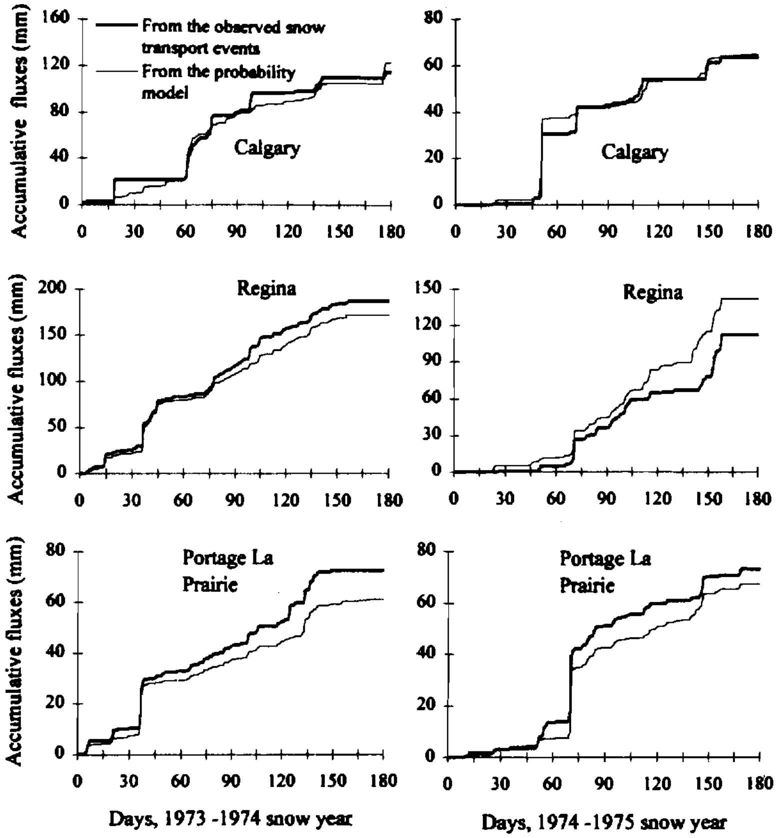

Figure 9. Annual accumulation of snow transport and sublimation fluxes estimated using the probability of occurrence of blowing snow with those estimated using the observed blowing snow events for Calgary, Regina and Portage La Prairie, 1973-1974 and 1974-1975 snow years. The fluxes are expressed as snow water equivalent and calculated using a version of the Prairie Blowing Snow Model [*Pomeroy et al.*, 1993]. November 1 is day 1 of the snow year.

approximation of the threshold wind speed for this condition, the actual wind speed minus 0.5 m/s was considered to be the threshold. PBSM was run hourly throughout the snow year with AES meteorological observations to calculate the snow transport and sublimation fluxes for a fallow field with 1000 m fetch distance. As blowing snow does not necessarily occur throughout the 1-hour period, the fluxes from PBSM multiplied by the probability are taken as the snow transport and sublimation fluxes for that hour, estimated from the probability model.

PBSM was run again to estimate the snow transport and sublimation fluxes from the blowing snow events observed by AES. PBSM was "turned on" only for the hour that "blowing snow" or "drifting snow" was recorded and given a probability of 1 for this hour. The cessation threshold wind speed was determined according to the minimum wind speed during the blowing snow event and the wind speed of the first hour after transport ceased. If the minimum wind speed during an event was less than or equal to the wind speed at the first hour after transport, the actual cessation threshold must be lower than the minimum. To find the actual cessation threshold in this circumstance, the minimum wind speed during the blowing snow event minus 0.5 m/s was taken as the cessation threshold wind speed. If the minimum was greater than the wind speed of the first hour after transport, the average of the two was taken as the cessation threshold wind speed.

The cumulative snow transport and sublimation fluxes estimated from the probability/threshold models are compared with those from the observed blowing snow events (Figure 9). The cumulative fluxes estimated by the two techniques concur throughout each of the two snow years at the three locations. This indicates that the probability model accurately estimated the timing of major blowing snow events and the frequency of occurrence of blowing snow. The cumulative fluxes were underestimated for Portage La Prairie in both years and overestimated for Regina and Calgary in the moderate snowfall year with an underestimate in the extreme snow and wind year (Figure 9). These small under or over estimates of blowing snow fluxes seem primarily due to under or over estimates of the frequency of occurrence of blowing snow (Figure 8). The estimate errors are expected since the probability is statistically derived from data of the 16 prairie locations and factors other than wind speed, air temperature, and snow age are not included in the probability model.

Conclusions

The probability of occurrence of blowing snow when there is snow on the ground increases with increasing wind speed and decreases with increasing ambient air temperature and increasing snow age. At low temperatures (<-25°C), however, the probability decreases with decreasing temperature. The probability distribution of occurrence of blowing snow with respect to wind speed approximates a cumulative normal distribution. The mean and variance of wind speed for this distribution index snow resistance and sensitivity to transport, and define the cumulative normal probability distribution. The mean wind speed increases with increasing air temperature and snow age, except at low air temperatures where the relationship reverses. The variance of wind speed increases with increasing air temperature. The probability model is developed statistically but with a physical basis and can be confidently applied within its observation range for air temperatures greater than -35°C and wind speeds greater than 3 m/s and less than 20 m/s. The frequency of occurrence of blowing snow calculated by the model agrees well with that determined from meteorological observations on the Canadian prairies. The performance of the model proves satisfactory when used with the PBSM to estimate snow transport and sublimation fluxes and will permit application of the PBSM with data from standard meteorological stations around the world or nested in land surface schemes of global circulation models and numerical weather prediction models.

Acknowledgments. The authors wish to thank D.M. Gray, Chairman of the Division of Hydrology, for his encouragement and support of this work. Dell Bayne was instrumental in digitizing the extensive "remarks column" drifting snow data from microfilms of daily synoptic reports of the Atmospheric Environment Service (AES). The authors kindly thank Temple Murray, Secretary, Hydrological and Aquatic Sciences Division, NHRI for typesetting this paper in camera ready format. This study is indebted to the weather observers of Environment Canada for their years of careful manual observations, the Canadian Global Energy and Water Cycle Experiment (GEWEX) Programme, Climate Research Network, Land Processes Node (AES), Natural Sciences and Engineering Research Council of Canada, and the Hydrological and Aquatic Sciences Division, National Hydrology Research Institute, Environment Canada for funding provided.

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(Received December 23, 1996; revised May 1, 1997; accepted May 21, 1997.)