ESTIMATING SNOW TRANSPORT FROM WIND SPEED RECORDS: ESTIMATES VERSUS MEASUREMENTS AT PRUDHOE BAY, ALASKA

by

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INTRODUCTION

To be effective and economical, snow fence systems must have sufficient capacity to store all of the snow transported over the design year. The only proven method for estimating snow transport is a conceptual model for the evaporation of blowing snow that relates transport to fetch distance and relocated precipitation (Tabler, 1975; 1987). The proportion of precipitation relocated by the wind is most readily estimated for windy locations where precipitation is the primary factor limiting snow transport. The proportion of snowfall relocated by the wind is more difficult to estimate where there is more snow on the ground than there is wind to move it. In these locations, snow transport could be better estimated from historical wind records if the relationship between wind speed and snow transport were known. Despite the considerable attention given to this problem, there is no proven equation relating wind speed to snow transport summed to a height meaningful for drift control. This paper describes a new process-based equation relating snow transport in the first 5 metres above the snow surface to 10-m wind speed, and compares estimates derived from this equation with measured snow accumulation behind snow fences at Prudhoe Bay, Alaska.

CHARACTERISTICS OF SNOW TRANSPORT

Modes of Transport

The three modes of snow transport generally recognized are "*creep*," "*saltation*," and "*turbulent diffusion*" (Mellor, 1965). "*Creep*" refers to particles rolling along the surface; these particles are too large to be lifted off the surface under existing wind conditions. Migrating snow waves or dunes develop from creeping snow, a condition occurring when there is a source of large snow grains from a snowfall that has aged for a few days before the onset of winds. These dunes migrate downwind at a rate proportional to the wind speed. With a 10-m wind speed averaging 8 m/s, snow waves have been observed to move at about 5 m/h, and to transport about 45 kg/h per metre of width across the wind (Tabler, unpublished data). Kobayashi (1971) reported snow wave celerities of 1.2 to 6 m/h, wavelengths from 3 to 15 m, and heights from 0.05 to 0.2 m. Although creeping particles comprise one-fifth to one-quarter of total transport for blowing sand (Raudkivi, 1976), a much smaller proportion of snow is transported in this mode, except at the lowest wind speeds.

"*Saltation*" refers to the way snow particles appear to jump along the surface, and this is the dominant mode of travel for particles that are too heavy to be suspended in the air. Although trajectories of saltating particles vary with particle size, wind speed, and surface conditions, a typical "jump" is a parabolic arc 1 cm high and 20 cm long. Most saltating particles attain a maximum trajectory height ranging from a few millimetres to 5 cm (Maeno et al., 1985; Male, 1980; Kikuchi, 1981). Many investigators believe that saltation is the dominant mode of transport.

"*Turbulent diffusion*" refers to the mechanism by which particles are transported in "suspension" without the periodic surface contact typifying saltation. Saltation is the source of particles that become "suspended" when the time-averaged drag force imposed by upward-moving air offsets the gravitational force. Because drag force is proportional to the square of the diameter, whereas mass increases with the cube of this dimension, diffusion favors smaller particles, and suspended particles are therefore smaller than those moving in saltation. As suspended particles become smaller through evaporation, they tend to be carried higher above the surface. These sorting processes cause particle size to decrease with increasing height above the surface. Although there are differing opinions regarding the proportion of snow transported by diffusion and saltation (Radok, 1977), the most recent theories suggest that suspension is the dominant mode of transport (Pomeroy, 1988).

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Wind Speed Profile

Wind speed increases with height due to the diminishing drag exerted by the earth's surface. Although the shape of the wind profile close to the snow surface is uncertain, a mathematical representation of the wind profile in blowing snow above the saltation layer is

$$u = (u_*/k)\ln(z/z_o) \quad (1)$$

where u is wind speed at height z above the surface, u_* is the shear velocity (defined as the square root of the surface shear stress divided by the air density), z_o is the height at which the wind speed is zero (termed the aerodynamic roughness height), and k is von Kårmån's constant, usually taken as 0.4. Equation (1) does not fit measured wind profiles when evaporation from blowing snow particles is sufficient to induce a steep temperature gradient near the surface (Schmidt, 1982). Representative values for z_o are 0.01 mm over smooth ice, and 0.2 mm over a smooth snow surface without blowing snow. In the case of blowing snow or sand, the saltating particles create additional drag that changes the shape of the wind profile (Owen, 1964). In terms of Equation (1), saltating snow particles create a dynamic surface roughness, the height of which increases with wind speed. Because ascensional velocities are of the order u_*, maximum trajectory height should be proportional to $u_*^2/2g$, where g is gravitational acceleration. Measured saltation heights in both blowing sand and snow are consistent with the approximation

$$h_s \approx u_*^2/12.25 \quad (2)$$

where h_s (m) is the thickness of the saltation layer, and u_* is in m/s (Greeley and Iversen, 1985; Pomeroy, 1988). Saltation roughness is reflected in the aerodynamic roughness length whereby

$$z_o = u_*^2/C_1 \quad (3)$$

where C_1 is the coefficient of proportionality. For z_o in metres and u_* in m/s, Owen (1964) found C_1 = 950 fitted data reported for sand and soil, and Kind (1976) proposed the same value for snow. Subsequent wind profile measurements have shown C_1 = 740 m/s^2 for snow cover on a frozen lake (Tabler, 1980), 312 m/s^2 for shortgrass foothills in Wyoming (Tabler and Schmidt, 1986), and 163 m/s^2 for snow-covered fallow fields on the Canadian prairies (Pomeroy, 1988). It is therefore apparent that C_1 varies with surface conditions.

Snow Transport Rate

The wind speed at which snow particles start to move depends on the condition of the snow cover and density of the air, the latter varying with atmospheric pressure and temperature. At 2500 m elevation and -7°C, fluffy dendritic snow crystals will begin to move when the 10-m wind speed (designated as u_{10}) reaches about 6 m/s, while a snow surface hardened by wind and sun can resist erosion with u_{10} > 25 m/s. The threshold for cessation of blowing snow is less variable. Snow transport ceases at about u_{10} = 7 m/s at 2500 metres and -7°C, and at about 5 m/s at sea level and -30°C. Threshold shear velocities of about 0.28 m/s have been reported for the Antarctic (Budd, et al., 1966; Liljequist, 1957), and for Wyoming (Tabler, 1980). Kind (1981) presents data demonstrating the relationship between threshold shear velocity and surface hardness.

Factors affecting snow transport rate include the vertical distribution of wind speed, hardness of the snow surface, proportion of surface covered by snow, size and density of roughness features protruding above the snow surface, air density, snow particle size, and fetch distance. Considering these sources of variability, it is hardly surprising that different empirical equations have been proposed to relate snow transport to wind speed (Table 1). Although there is general consensus that transport rate in the first 2 metres above the ground is approximately proportional to the cube of the wind speed, more complex relationships are needed to account for the effects of snow surface conditions on the mechanics of particle transport, and the mechanics of turbulent diffusion in relation to transport at greater heights.

Transport rate depends strongly on surface roughness and hardness. A hard snow surface exhibits greater threshold speeds, but transport rate for a given wind speed will be larger than for a fresh snow surface because less momentum is lost in friction between particles and the surface (Schmidt, 1986). Field measurements of transport in the lowest 0.5 m verified the relationship

$$q = (\rho_a/g)(a/\tan\alpha)(u_* - u_{*t})(u_*^2 - u_{*t}^2) \quad (4)$$

where q is total transport rate in the first 0.5 m above the surface (kg/m·s), ρ_a is air density (kg/m^3), g is gravitational acceleration (m/s^2), and u_{*t} is threshold shear velocity (m/s). The a term is a saltation speed parameter, and $\tan\alpha$ is a coefficient of friction between the moving particles and the surface. The ratio $a/\tan\alpha$ declines exponentially with increasing intrinsic surface roughness; for example, $a/\tan\alpha$ = 30 for z_o = 0.04 mm, and $a/\tan\alpha$ = 5 for z_o = 0.3 mm. The latter ratio is appropriate for snowcover on land (as oppposed to ice) surfaces.

Table 1

Empirical expressions for mass flux of blowing snow as a function of wind speed. u is wind speed (m/s) at height (metres) indicated by subscript. Transport rate, q, is in kilograms of snow per metre of width across the wind, per second, totaled over heights indicated.

Investigator	Height -m-	Formula	Comments
Mel'nik (1952) (Dyunin, 1954)	0-2	$q = 0.0000215u_{11}^3$	
Komarov (1954)	0-2	$q = 0.00001083u_1^{3.5} - 0.0006667$	
Budd, Dingle, and Radok (1966)	0.001-300	$\log q = -1.8188 + 0.0887u_{10}$	
D. Kobayashi et al. (1969)	Saltation	$q = 0.00003u_1^3$	
D. Kobayashi (1972)	Saltation	$q = 0.00003(u_1 - 1.3)^3$	
Dyunin and Kotlyakov (1980)	0-2	$q = 0.00034(u_{0.2} - 3)^3$	
Dyunin and Kotlyakov (1980)	0-2	$q = 0.000077(u_{10} - 5)^3$	
M. Takeuchi (1980)	0-2	$q = 0.0002u_1^{2.7}$	"old firm snow"
M. Takeuchi (1980)	0-2	$q = 0.0000029u_1^{4.16}$	"settled dry snow"

Snow Transport Equation

A process-based transport model and computer algorithm, termed the Prairie Blowing Snow Model (PBSM), allows saltation and suspension transport to be partitioned (Pomeroy, 1988; Pomeroy, 1989; Pomeroy and Gray, 1990). According to this model, total mass flux of saltating snow, q_{salt}, is given by

$$q_{salt} = 0.68\,[\rho_a/(u_*g)](u_{*t}u_*^2 - u_{*t}u_{*n}^2 - u_{*t}^3) \tag{5}$$

where u_{*n} is the friction velocity associated with the fixed roughness elements protruding through the snow surface. As an engineering approximation, Pomeroy (1988) found measured transport rates (kg/m· s) at a fallow field site having unlimited fetch and uniform snow cover, to be represented by

$$q_{salt} \simeq 0.000753\, u_{10}^{1.295} - 0.008456 \tag{6}$$

applicable for wind speeds $\geq$ 6.5 m/s. An approximation for "suspension" transport in the first 5 m above the surface was derived using regression analysis to relate this quantity, as computed from the PBSM, to u_{10}. Transport rates, q_{susp} (kg/m· s), computed at 0.5 m/s increments of u_{10} over the range 6.5- to 25 m/s, were approximated by

$$q_{susp} \simeq u_{10}^{4.13}/674100 \tag{7}$$

Finally, regression analysis was used to derive an approximation for total transport in the first 5 m above the surface, $q_{0\text{-}5}$ (kg/m· s), calculated as the sum of Equation (6) and "suspension" transport as computed from the PBSM over the same range and incrementation for u_{10} as described above:

$$q_{0\text{-}5} \simeq u_{10}^{4.04}/458800 \tag{8}$$

Equation (8) is applicable for wind speeds $\geq$ 6.5 m/s, the threshold condition of Equation (6), and should provide a method for estimating snow transport from wind data when there is sufficient snow on the ground to achieve equilibrium transport.

VALIDATION OF EQUATION

It was possible to test Equation (8) at Prudhoe Bay, Alaska, where the requirement for unlimited snow on the ground is usually met. Detailed wind data are available, and actual snow transport can be inferred from measured snow accumulation at tall snow fences. Comparisons of estimated and measured snow transport are possible for four years (1986-89) when snow fence drifts were measured.

The snow accumulation season is defined as the period of snowpack growth extending from the first snowfall which does not completely melt, to the time of peak snow water-equivalent accumulation. The accumulation season is delimited by the dates when average air temperature reaches $0^{o}C$, as computed from mean monthly temperatures (Tabler, 1988). Using this criterion, the snow accumulation season at Prudhoe Bay extends from about mid-September to early June. For comparing estimated and measured transport, the period October 1 to May 15 was selected as being representative of dates when snow on the ground would normally be available for relocation.

Transport Estimated from Wind Data

Wind data for this study were from the Prudhoe Bay Airstrip (PRB), located approximately 7.5 km NNE of Deadhorse. Wind is measured with two propeller-type anemometers mounted 5 m above the ground, one installed near each end of the runway. Observers determine mean wind speed and direction by visually observing the dial-type indicators for a 5-minute period, and averaging readings from the two instruments. Peak gusts are those occurring over 15 minutes of observation. Observations are made hourly from about 0600 to 1800 LST, with supplemental observations when required for aircraft operations.

For the wind analyses reported here, the number of observations from October 1 to May 15 ranged from 3060 in 1988-89, to 3497 in 1986-87. The 12-hour observation period used at the airstrip therefore constitutes a 50% sample of 24-hour conditions, and should be representative because there is no appreciable diurnal wind variation at Prudhoe Bay, as will be discussed later in this paper.

Snow transport was computed from the frequency distributions of wind speed / direction using seventeen wind speed classes (i.e., calm, 1-4, 5-8, ... >60 knots) and sixteen direction classes. Although Equation (8) is strictly valid for $u_{10} \geq 6.5$ m/s, the relationship was also used to estimate transport for the 9- to 12-knot (4.6 - 6.2 m/s) class. Winds below 9 knots (4.6 m/s) were assumed not to contribute significant snow transport. For all other wind speed/direction classes having mid-class speed u_i (m/s), total transport to 5 m, q_i (kg/m· s), was calculated as

$$q_i \simeq (n_i/N)(D)(86400)\{(1.1)(u_i)\}^{4.04}/458800 \tag{9}$$

where n_i is the number of observations in the ith class, N is the total number of observations over the snow accumulation season, and D is the number of days in the snow accumulation season (227 for a 365-day year). The (1.1) multiplier for wind speed adjusts the speeds measured at 5-m height to the 10-m value required in Equation (8). Over the 4 years used for the study, there were no observations of wind speeds in excess of the 57- to 60-knot (29-31 m/s) class. Total transport was calculated as the sum of the q_i over wind direction classes NNE through SSE for east winds, and SSW through NNW for west winds, for comparison with measured snow accumulation.

Snow Accumulation Measured at Snow Fences

Trapping efficiency is the term describing the proportion of the incoming snow transport, from the surface to the top of the fence, that is collected by the fence. *Absolute* trapping efficiency compares what is trapped by the fence to the total transport from the snow surface to the top of the atmosphere. Although there is no way to measure total transport, the snow caught by tall fences (taller than 3.6 m or so) can be considered as a reasonable approximation for engineering applications because of the distribution of blowing snow with height, as decribed by Mellor (1965); Budd, Dingle and Radok (1966); Mellor and Fellers (1986); and Tabler, Pomeroy, and Santana (1990).

Although it is reasonable to expect trapping efficiency to vary with wind speed, no data are available to quantify such a relationship. Another reasonable expectation is that efficiency should decline as a fence fills with snow, and past studies provide a first approximation for this relationship. Because it is difficult to measure snow transport, indirect methods have been used to determine trapping efficiency, such as comparing the quantity of snow caught in two or more rows of fences. Results from such studies (Figure 1) suggest that the trapping efficiency of a fence declines in a roughly parabolic fashion from an initial value of about 95%. An approximation for the relationship in Figure 1 is

$$E \simeq 0.95(1 - S^2)^{0.5} \tag{10}$$

where E is trapping efficiency expressed as a fraction, and S is snow accumulated by the fence relative to its ultimate snow storage capacity:

$$S = q_s/q_c \tag{11}$$

where q_s is the mass of snow accumulated by the fence, and q_c is ultimate storage capacity. Snow storage capacity of 50%-porous horizontal-slat fences is given by

$$q_c = 8.5\,H^{2.2} \tag{12}$$

where q_c is in tonnes per metre of fence length, and H is vertical fence height in metres (Tabler, 1989).

The *average* trapping efficiency, $\overline{E}$, of a fence over a winter, can be estimated by integrating the area under the curve given by Equation (10), from $S = 0$ to S_e, the value at the end of the season:

$$\overline{E} = (1/S_e)(0.95)\{0.5S_e(1 - S_e^2)^{0.5} + 0.5\,\mathrm{Sin}^{-1}(S_e)\} \tag{13}$$

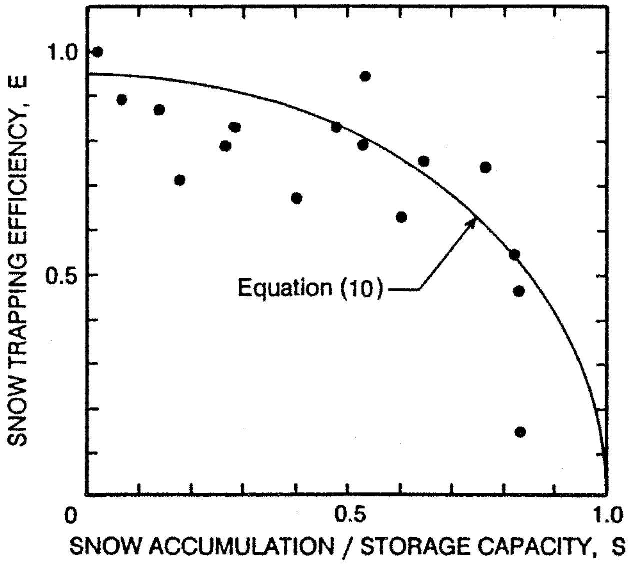

Figure 1. Snow trapping efficiency of a 50% porous horizontal-board fence as a function of snow storage relative to capacity. Data are those reported by Tabler (1974), adjusted for revised estimates of snow fence storage capacity.

At Prudhoe Bay, as at other locations on Alaska's North Slope, approximately two-thirds of the snow transport is associated with easterly winds, and one-third with westerly winds (Benson, 1982). If snow accumulation at a fence is to be related to drifting from a specific direction, the fence must be protected from snow transported from the opposite direction.

The first permanent tall snow fence in the Prudhoe Bay area was built on the east side of the ARCO Operations Storage Pad (AOSP) in 1984. This fence was originally 3.6 m tall and 300 m long, and consisted of horizontal 5- x 20-cm boards spaced 20 cm apart, bolted to steel pipes embedded in the permafrost. The pipe supports were installed at a 15° angle with the top of the fence inclined downwind. As a result of differential seasonal thawing, the inclination has gradually increased to 38° in April, 1989, with a corresponding decline in vertical fence height. The storage pad has a rectangular 300- x 600-m plan, with the long dimension oriented east-west. The elevated storage platforms and stores collect blowing snow from the west, so that deposition at the snow fence is essentially limited to snow transported by easterly winds.

Beginning in 1986, snow accumulation at the AOSP fence has been measured each spring, allowing comparison with snow transport estimated from Equation (9). The snowdrift at the fence has been cross-sectioned by differential leveling, with measurement dates ranging from mid-March to the end of May. Snow depths are computed from elevations measured at 2- to 3-m intervals along a single transect located about 80 m from the south end of the fence.

Additional snow fences, having heights ranging from 4.4- to 4.9 m and utilizing plastic fencing materials with 50% porosity, were built at other locations during the 1987-88 winter. Snow accumulation measured at these fences April 25-29, 1989, allow comparison of measured and estimated transport for both east and west winds. Locations and descriptions of the snow fences used for this comparison are presented in Table 2.

Table 2

Location and description of snow fences where snow accumulation was measaured April 28-29, 1989, for validation of snow transport equation (PRB = Prudhoe Bay Airstrip).

Fence I.D.	Location	Distance from PRB	Fence height	Fence length
			-m-	-m-
	Fences exposed to snow transported by easterly winds:			
AOSP	ARCO Operations Storage Pad, east side	4 km NW	3.6 - 2.9	300
GC2-E2	Gathering Center 2, east side	21 km WNW	4.6	309
LPC	Lisburne Production Center, east side	6 km NNW	4.6	400
L2-E	Lisburne Drill Site Pad L-2, east side	7 km NNW	4.6	509
	Fences exposed to snow transported by westerly winds:			
GC2-W3S	Gathering Center 2, west side	21 km WNW	4.3	242
L2-W	Lisburne Drill Site Pad L-2, west side	7 km NNW	4.6 - 4.9	305
L5-W	Lisburne Drill Site Pad L-5, west side	10 km NNE	4.6 - 4.9	305

Snow depths were converted to water-equivalent using an empirical depth/density relationship for drifted snow proposed by Tabler (1985):

$$\rho_s = 522 - (304/1.485\,y)\{1 - \exp(-1.485\,y)\} \tag{14}$$

where ρ_s is snow density (kg/m^3) before the onset of melt, and y is snow depth in metres. To test the applicability of this equation, snow density was sampled in 1989 at the AOSP fence and two other locations, using a standard Federal (Mount Rose) snow tube. Sample weights were multiplied by 0.91 to correct for the over-run known to be associated with the Federal sampler (Tabler, 1985). As shown in Figure 2, the density of snow deeper than about 1 m was in reasonable agreement with Equation (14). The lower density of shallower snow is attributed to low-density depth hoar and voids associated with destructive metamorphism, suggesting that the lower portion of the snowpack did not consist of relocated snow. Sampling deep snowdrifts is very difficult and time consuming, and a large number of samples is required to keep sampling errors within acceptable limits. The results obtained here are sufficient to define the potential error in using Equation (14) to estimate snow densities.

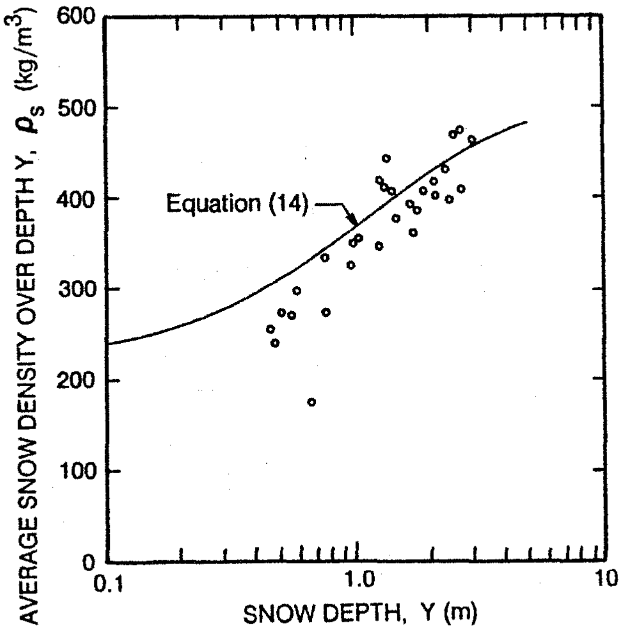

Figure 2. Density of snow fence drifts at Prudhoe Bay as sampled with a Federal snow sampler on April 30, 1989, and the empirical relationship for drifted snow prior to onset of melt given by Equation (14).

Results and Interpretation

Measured snow accumulation and estimated snow transport are compared in Table 3. Snow accumulation in 1986 through 1988 was that measured at the AOSP fence; no other fences were available to allow measurements of west wind transport. Snow accumulation for 1989 is the average of measurements at three fences for each direction, shown with 95% confidence intervals. The fences were those described in Table 2 having heights ≥ 4.6 m. The AOSP fence was not used in 1989 because of its smaller storage capacity.

Table 3

Measured snow accumulation at snow fences and snow transport calculated from wind records using Equation (9). Snow accumulation for 1986-1988 was that measured at fence AOSP. Measured snow accumulations in 1989 are averages of three fences for each direction, shown with 95% confidence intervals. *nm* = no measurement.

	East wind snow transport			West wind snow transport		
Measurement date	Measured snow accumulation, M	Estimated snow transport, E	E / M	Measured snow accumulation, M	Estimated snow transport, E	E / M
	-t/m-	*-t/m-*		*-t/m-*	*-t/m-*	
23 May 1986	108.2	108.8	1.01	nm	---	---
6 May 1987	52.5	52.0	0.99	nm	---	---
16 Mar 1988	76.1	136.3	1.79	nm	---	---
29 Apr 1989	91.1 ± 6.8	80.7	0.89	102.3 ± 14.0	348.3	3.40

For the comparisons in 1986 and 1987, snow transport was estimated utilizing wind data for the period October 1 through May 15. For 1988 and 1989, however, estimated transport was computed using wind data from October 1 to the date snow accumulation was measured.

Estimated snow transport for east winds was within 11% of measured snow accumulation for three of the four years, the differences being within the limits of experimental error. We believe that the overestimate for snow transport over the 1987-88 winter reflects the fact that snowfall early in the winter was insufficient to meet the requirement for unlimited snow supply. This conclusion is supported by journal entries and precipitation records from the Prudhoe Bay Airstrip (Table 4). Because the precipitation gauge is operated without a wind shield, the recorded values are probably one-third to one-half of actual precipitation (Benson, 1982; Tabler et al., 1990); however, the data should be indicative of early season snow availability.

The difference between measured snow accumulation and estimated snow transport for westerly winds over the 1988-89 winter is both striking and instructive. Most of the west wind transport occurred during an unusually severe windstorm which began at 0330 LST 25 February 1989, and continued until 2400 h 26 February. During this time, gusts to 49 m/s were recorded at PRB. Poor visibility and flying debris prompted the observer to remain in the tower, where he continued to make observations. As a result, wind records for the 1988-89 winter are biased by the greater sampling frequency during this wind storm. Removing the 13 extra readings taken over the two-day storm reduces the estimate for west wind transport to 159.3 t/m, or 56% more than the measured snow accumulation. This incident demonstrates the errors that can arise when using historical wind records to estimate snow transport.

Table 4

Water-equivalent precipitation (mm) recorded at Prudhoe Bay Airstrip.

Month	Winter			
	1985-86	1986-87	1987-88	1988-89
September	7	2	1	12
October	17	10	8	12
November	0	3	3	3
December	2	1	4	6
January	2	1	0	11
February	5	2	12	19
March	5	1	5	3
April	0	4	0	3
May	4	0	3	2

Error Analysis

The most significant sources of error in this comparison are described below in approximate order of potential significance:

1. *Limited snow availability:* Equation (8) is only applicable when snow is unlimited, and this requirement is the greatest source of uncertainty in the comparison. Although the existence of unlimited snow is a reasonable assumption at Prudhoe Bay for the calendar dates used in this study, it is unlikely that such conditions always prevailed. This error would lead to snow transport being overestimated, as illustrated by the comparison for 1987-88.

2. *Limitations of Equation (8):* Although derived from a process-based model, the equation itself is an empirical approximation for transport averaged over a range of snow surface conditions. Predictions for a specific event would be subject to large errors, but estimates for seasonal transport should sum to zero. It is expected, however, that Equation (8) might require adjustment for application in a specific environment.

3. *Snow escaping fences:* As calculated from Equation (14), trapping efficiencies of the snow fences averaged about 87-, 93-, 92-, and 93%, respectively, for the 4 years of study. This suggests that the snow fence measurements underestimated snow transport by 7- to 13%.

4. *Wind sampling errors:* Diurnal wind variation can be determined using the data recorded at Well Pad A since October, 1986, as part of the air quality monitoring program operated by ENSR Consulting and Engineering. The anemometer at Pad A is at 10 metres height; wind speed and direction is scanned electronically once each second to compute 5-minute averages, from which hourly means are computed. Plots of wind data versus time for months selected at random suggest no diurnal variation for wind speeds above the snow transport threshold--a conclusion shared by Stephen R. Andersen, Meteorologist for ENSR Consulting and Engineering (personal communication). The absence of diurnal wind variation suggests that observations made during daylight hours should provide an unbiased sample of daily wind speed. As demonstrated by the windstorm in February, 1989, however, extreme events can indirectly lead to biased sampling. For this comparison, it was possible to quantify the bias resulting from the February storm by referring to the original records and deleting observations made outside of the normal operational schedule. Although there may have been other instances that were unidentified, the potential for error in this comparison is considered to be comparable with that of other sources.

   The potential error arising from the method of visually averaging wind speed over a 5-minute period has probably been investigated elsewhere, but is not considered to be significant compared to other sources of error.

5. *Snow density:* Samples obtained in 1989 (Figure 2) suggest that Equation (14) may overestimate density of snow shallower than 1 m or so by as much as 15%. This systematic error would result in snow transport being overestimated by 10% or less.

6. *Snowdrift measurements:* Uniformity of snow profiles and ground surface suggest that sampling and measurement errors combined would contribute less than ± 10%.

7. *Resolution of wind data:* The 4-knot (2.06 m/s) wind speed classes used in this study are sufficiently narrow and inclusive to avoid significant computational errors. During the four years used to compare estimated and measured transport, there were no observations in excess of the 57- to 60-knot (29-31 m/s) class. The threshold for snow transport used in this study (u_5 = 9 knots ≈ 4.6 m/s) was determined from surface weather records at Prudhoe Bay which

report drifting snow with average wind speeds as low as 10 knots (5.1 m/s). Although Equation (8) is strictly valid only for $u_{10} \geq 6.5$ m/s, we believe that snow transport for the 9- to 12-knot (4.6- to 6.2 m/s) class is more realistically estimated by Equation (8) than by zero. The small proportion of total transport contributed by this class, as shown in Table 5, suggests that the error from this source would be less than 5%.

APPLICATIONS

Equation (8) provides a basis for determining the required storage capacity of snow fences and other drift control measures, and in the form of Equation (9), can be used to develop snow transport frequency distributions. This information can be used to estimate return periods, and to define the directional distribution of snow transport--information of primary importance for designing snow control measures.

Estimated Average Snow Transport at Prudhoe Bay

All historical wind data for Prudhoe Bay Airstrip, covering the period November, 1968 through May, 1989, were tabulated by years using the same conventions as previously described. Snow transport distributions were then computed for each year using Equation (9), and the results averaged to obtain the 21-year average distribution presented in Table 5. Estimated transport by easterly winds (N through SSE) is 160 ± 44 t/m (95% confidence interval), with a mean direction 78 ± 4^{o}. Transport from the west (S through NNW) is 109 ± 45 t/m, mean azimuth 253 ± 5^{o}. Easterly winds therefore contribute about 60% of the total snow transport.

CONCLUSIONS

1. The following relationship, derived from Pomeroy's (1988) process-based model for wind-transported snow, is a valid approximation for season-long snow transport in the lowest 5 m if snow supply is unlimited:

$$q_{0\text{-}5} \simeq u_{10}^{4.04}/458800$$

2. When basic requirements for snow conditions and wind data are satisfied, the above relationship provides reasonably close estimates of seasonal snow transport over heights 0-5 m at Prudhoe Bay. No other known formulation relating wind speed to transport provides approximations that agree as well with measured snow accumulation.
3. Large errors can result from biased sampling of wind speed, and failure to satisfy the requirement for unlimited snow.
4. Although future experience may suggest the need for adjusting the coefficient in Equation (8) for regional conditions, the present formulation provides reasonable estimates for engineering applications.
5. Analysis of historical wind records at Prudhoe Bay for 1968-89 provides the following estimates for snow transport, shown with 95% confidence intervals:

easterly winds: 160 ± 44 t/m, mean azimuth 78 ± 4^{o}
westerly winds: 109 ± 45 t/m, mean azimuth 253 ± 5^{o}

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Table 5

Mean seasonal snow transport (q_{0-5}, kg/m) versus direction at Prudhoe Bay Airstrip as computed using Equation (9) and wind records from 1968-89.

Wind azimuth	Direction	Wind speed class (knots)																
		1-4	5-8	9-12	13-16	17-20	21-24	25-28	29-32	33-36	37-40	41-44	45-48	49-52	53-56	57-60	>60	Total
(Degrees, TN)		kg/m																
348.75 - 011.25	N	0	0	74	94	122	10	75	0	0	0	0	0	0	0	0	0	376
011.25 - 033.75	NNE	0	0	228	256	243	39	152	38	0	0	0	0	0	0	0	977	1934
033.75 - 056.25	NE	0	0	1243	3223	3519	1151	1303	345	504	3434	0	841	0	0	0	0	15564
056.25 - 078.75	ENE	0	0	1999	8873	17563	9497	10781	7889	3869	1966	479	1723	0	0	0	0	64638
078.75 - 101.25	E	0	0	1609	5707	14036	8417	13027	9813	6283	3954	1109	0	0	0	0	0	63955
101.25 - 123.75	ESE	0	0	355	1036	2055	1737	1710	1477	1617	1072	683	0	0	0	0	0	11740
123.75 - 146.25	SE	0	0	105	104	138	0	34	0	0	0	0	0	0	0	839	0	1219
146.25 - 168.75	SSE	0	0	25	33	12	35	0	0	0	0	0	0	0	0	0	0	106
168.75 - 191.25	S	0	0	51	76	117	0	0	0	0	0	0	0	0	0	0	0	244
191.25 - 213.75	SSW	0	0	215	390	516	230	69	105	98	0	253	0	0	0	0	570	2446
213.75 - 236.25	SW	0	0	916	2911	3419	1282	1112	970	0	155	0	0	0	0	849	0	11511
236.25 - 258.75	WSW	0	0	1971	5265	7832	3469	2785	1698	1590	903	400	1093	509	2076	6450	0	36043
258.75 - 281.25	W	0	0	1703	5217	9421	6528	9527	5827	4076	4964	1682	1476	1120	700	466	1027	53734
281.25 - 303.75	WNW	0	0	200	399	514	426	480	425	337	86	0	0	468	0	0	0	3335
303.75 - 326.25	NW	0	0	33	66	37	0	36	0	0	0	0	0	0	0	0	0	171
326.25 - 348.75	NNW	0	0	24	22	8	0	0	0	0	0	174	0	0	0	839	0	1067
000.00 - 360.00		0	0	10751	33672	59552	32821	41089	28586	18373	16534	4781	5134	2097	2776	9443	2574	268083

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