2004

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Martha Shulski
University of Nebraska–Lincoln, mshulski3@unl.edu

Mark W. Seeley
University of Minnesota

Shulski, Martha and Seeley, Mark W., "Application of Snowfall and Wind Statistics to Snow Transport Modeling for Snowdrift Control in Minnesota" (2004). *Papers in Natural Resources*. 589.
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Journal of Applied Meteorology
November 2004, Vol. 43, No. 11

Application of Snowfall and Wind Statistics to Snow Transport Modeling for Snowdrift Control in Minnesota

MARTHA D. SHULSKI

Geophysical Institute, University of Alaska Fairbanks, Fairbanks, Alaska

MARK W. SEELEY

Department of Soil, Water, and Climate, University of Minnesota, Saint Paul, Minnesota

(Manuscript received 4 May 2003, in final form 26 April 2004)

ABSTRACT

Models were utilized to determine the snow accumulation season (SAS) and to quantify windblown snow for the purpose of snowdrift control for locations in Minnesota. The models require mean monthly temperature, snowfall, density of snow, and wind frequency distribution statistics. Temperature and precipitation data were obtained from local cooperative observing sites, and wind data came from Automated Surface Observing System (ASOS)/Automated Weather Observing System (AWOS) sites in the region. The temperature-based algorithm used to define the SAS reveals a geographic variability in the starting and ending dates of the season, which is determined by latitude and elevation. Mean seasonal snowfall shows a geographic distribution that is affected by topography and proximity to Lake Superior. Mean snowfall density also exhibits variability, with lower-density snow events displaced to higher-latitude positions. Seasonal wind frequencies show a strong bimodal distribution with peaks from the northwest and southeast vector direction, with an exception for locations in close proximity to the Lake Superior shoreline. In addition, for western and south-central Minnesota there is a considerably higher frequency of wind speeds above the mean snow transport threshold of 7 m s^{-1}. As such, this area is more conducive to higher potential snow transport totals. Snow relocation coefficients in this area are in the range of 0.4–0.9, and, according to the empirical models used in this analysis, this range implies that actual snow transport is 40%–90% of the total potential in south-central and western areas of the state.

1. Introduction

The topography, land use characteristics, and winter climate of the upper Midwest combine to produce an area that is particularly vulnerable to the problem of blowing and drifting snow on roadways. The Minnesota Department of Transportation (Mn/DOT) estimates that there are 4000 locations in Minnesota, totaling 1000 mi (1609 km), for which drifting snow on roadways is problematic (Gullickson et al. 1999). In these areas, driver safety, road degradation, and removal costs are of primary concern. Traveler safety is often severely compromised in the winter months by slick roads, reduced or eliminated shoulder, and poor visibility. In addition, scraping roads and infiltration of meltwater can result in a relatively rapid decline of road quality. Snow removal throughout the winter can be very costly at an average price of $1 per ton (907 kg), such as during the severe winter of 1996/97, when $215 million was spent in Minnesota on snow removal costs by local government units, and much of this cost resulted from replowing windblown snow (Gullickson et al. 1999). Moreover, many of these drifting problems occur in the same areas year after year.

This problem can be mitigated by the utilization of snow fences (either structural or living), which act as windbreaks to disrupt airflow and cause snow deposition (Plate 1971; Heisler and DeWalle 1988; McNaughton 1988). However, the placement of a snow fence, and the associated snowdrift, on the landscape greatly affects above-ground and subsurface moisture conditions (Shaw 1988). In arid regions, this snowdrift can provide a much-needed reservoir of water for use by crops during the growing season (Willis and Frank 1975; Dickey 1988), and it is shown that the effects of snow fences in general are positive, leading to an increase in crop quality and yield (Kort 1988). The use of snow fences is not a new concept (Finney 1934), but their effectiveness to improve transportation was greatly enhanced with snow transport and snowdrift modeling research and case studies (Tabler 1980; Martinelli et al. 1982; Jairell and Tabler 1985; Pomeroy et al. 1993; Schmidt and Jairell 1994; Schmidt et al. 1994). This work has

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Corresponding author address: Dr. Mark Seeley, Department of Soil, Water, and Climate, Rm. 439, Borlaug Hall, University of Minnesota, St. Paul, MN 55108.
E-mail: mseeley@soils.umn.edu

lead to the development of formal guidelines by Tabler (1994), which have proven to be effective as implemented by the Wyoming Department of Transportation.

The success of a snow fence and the snow storage capacity largely depends on fence height, porosity (in total and the vertical distribution), and setback distance from the problem area (Tabler and Jairell 1993; Tabler 1980, 1994). The correct determination of these variables is, of course, dependent on the quantity of windblown snow for the given problem area. The Mn/DOT has decided to utilize the mitigation strategy outlined by Tabler much more vigorously than they have in the past, when mixed results were achieved in the absence of knowledge about appropriate fence porosities and setbacks for constructed or living snow fences. It is acknowledged that their efforts in this regard are at least partially motivated by the financial losses incurred during the winter of 1996/97. The objectives of this study are to determine the interval in which blowing-snow events occur, known as the snow accumulation season (SAS), to examine wind frequency distributions for available locations in Minnesota, and to use site-specific climatological data to model snow transport.

2. Characteristics of snow transport

Snow movement is categorized by three modes of transport: creep, saltation, and turbulent diffusion (Mellor 1965, III-A3C). Particles that roll along the surface are generally too large to be lifted above the first few centimeters and move by creeping (Tabler et al. 1990; Tabler 1994). Saltating particles jump along the surface in parabolic arcs and often dislodge other particles in the process (Pomeroy and Gray 1990), and particles suspended in the air without surface contact travel by turbulent diffusion (Tabler 1973, 1975). The vertical distribution of snow particles in transit is highly skewed, with the greatest particle mass in the first few meters above the surface (Pomeroy 1989).

A given wind speed threshold must be attained before the shear stress is able to overcome the strength of snow particle bonds at the snow surface (Schmidt 1981; Pomeroy and Gray 1990). Li and Pomeroy (1997) observe snow transport on the Canadian prairies to be a function of air temperature, snow age, and whether the snow particles were wet or dry, with typical threshold speeds in the range from 7.5 m s^{-1} for fresh snow to 8.0 m s^{-1} for aged snow, with large variance within the same temperature regime. Other studies at locations in Wyoming and Alaska have reported that snow transport initiates at a speed of approximately 6.7 m s^{-1} (Schmidt 1981; Tabler et al. 1990).

Because of the complex physical processes that contribute to the transport (and evaporation) of blowing snow, transport estimates must often incorporate both theoretical and empirical methods. In addition, the limited availability of detailed meteorological data on the large scale may require the use of a simplified approach to estimate windblown snow. A model quantifying snow transport was developed by Mellor and Fellers (1986) in which a regression equation was used to relate particle mass flux to wind speed and height above the surface. Further analyses using both process-based (Pomeroy 1989) and empirically based (Tabler 1991) algorithms showed that, if there is an unlimited snow supply, the rate of snow transport in the first 5 m above the surface is a function of wind speed raised to a power. The potential snow transport over a season Qupot (kg m^{-1}) can be estimated using the following

$$\mathrm{Qupot} = (u_{i,j}^{3.8}/233\,847)(f_{i,j})(86\,400)(n), \qquad (1)$$

where $f_{i,j}$ is the frequency of observations in the ith speed class and jth direction class, n is the number of days in the season, and $u_{i,j}$ (m s^{-1}) is the midclass wind speed (Tabler 1994). This method divides wind data into speed and direction classes such that the cardinal direction of greatest snow transport can be determined. A summation over all wind classes yields the total wind-defined potential transport. One key assumption to the algorithm is an unlimited snow supply, which is generally not the case over a season; therefore, it is necessary to consider a conceptual model of snow transport that incorporates meteorological as well as landscape characteristics.

The total mass of blowing snow is known to be subject to substantial losses that are primarily due to evaporation and/or sublimation because of the large ratio of surface area to mass for snow particles (e.g., Komarov 1954; Dyunin 1959). Numerous studies have validated this theory with various numerical and empirical techniques (Benson 1982; Schmidt 1982; Pomeroy 1989). Tabler (1975) relates evaporation of snow particles to transport distance as

$$M/M_o = e^{-2(F/T)} \qquad (2)$$

where M is residual mass, M_o is initial mass, F is fetch distance (m), and T is maximum transport distance (m). The maximum transport distance represents an upper limit to the extent an average snow particle can travel before completely evaporating (or, in the case of extremely cold, dry air, sublimating). It is observed as approximately 3000 m, and, although it varies widely by event because of differences in temperature, humidity, and wind speed, it is shown to be stable when taken over the season as a whole (Tabler 1994). Research in Wyoming and Arctic Alaska validates the use of this approximation, which is rendered applicable for snow-control studies.

A conceptual snow transport model, which incorporates fetch distance, snowfall, snowfall density, and accounts for evaporative or sublimation losses of windblown snow [Eq. (2)], is expressed by Tabler (1994) as

$$\mathrm{Qt} = 1500\theta S_{\mathrm{we}}(1 - 0.14^{F/T}), \qquad (3)$$

where Qt is the total seasonal snow transport (kg m^{-1}), T is the maximum transport distance (assumed to be

3000 m), θ is a snow relocation coefficient, S_{we} is the seasonal snowfall in water equivalence (m), and F is fetch distance (m). If an unlimited fetch distance is assumed, Eq. (3) is referred to as the potential snow transport based on snowfall, or Qspot, where Qspot = $1500\theta S_{\mathrm{we}}$. The snow relocation coefficient is defined by Tabler (1994) as the fraction of snowfall that is relocated by the wind and is calculated as the ratio of Qupot to Qspot. This fraction also represents the ratio of wind-limited snow transport (Qupot) to snowfall-limited snow transport (Qspot). Typical seasonal values for the northeastern United States range from 0.2 to 0.3, while 0.7 is found for flat areas with low-growing vegetation in Wyoming and Siberia (Tabler 1994). Because these values are less than 1, it means that, over a season, wind energy is the factor that limits snow transport, rather than snow supply. Minnesota's geographic position and landscape characteristics, including geological features, topography, soils, watersheds, and vegetative types, produce an environment conducive to a wide range in snow relocation coefficients, lying somewhere within the limits found by Tabler (1994) for the northeastern and western states.

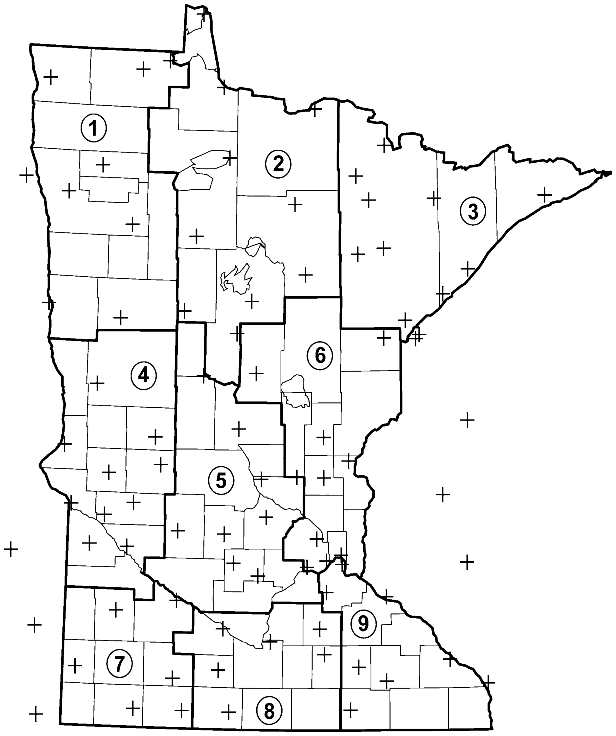

FIG. 1. Location of the ASOS/AWOS stations and climate division boundaries.

3. Climate data analysis

Aside from identifying the area along a roadway where blowing and drifting snow is problematic, the first step for snow control is to identify the SAS. The SAS is defined by Tabler (1988) to represent ''the period of drift growth beginning with the first blowing snow event that causes drifts persisting through the winter, and ends when snowdrifts reach maximum volume.'' Tabler's intent was to develop a simple algorithm that could be used where monthly local climatological data were available. The season is delimited by the dates on which the temperatures reach 0°C, as defined by the mean monthly temperature. Mean temperature data representing the last (first) month with values above freezing and first (last) month below freezing are used to extrapolate a snow-season onset (end) date using the following:

$$n = \frac{30T_+}{T_+ - T_-}, \tag{4}$$

where T_+ is the mean temperature of the above-freezing month (°C), T_- is the mean temperature of the below-freezing month (°C), and n is the number of days from the middle of the above-freezing month to the freezing date. To obtain the onset date in the autumn, n is added to the middate of the above-freezing month. The end date in the spring is calculated by subtracting n from the middate of the above-freezing month.

Daily maximum and minimum temperature data from cooperative observing locations throughout Minnesota (Summary of the Day, available from National Climatic Data Center) were averaged to obtain a daily mean temperature. Time of observation for these measurements is critical for obtaining an accurate mean daily temperature, as studied by Baker (1975); therefore, a correction factor (corresponding to a coefficient appropriate to the hour that maximum and minimum temperature observations were made) was applied to the temperature data. The period of 1971–96, representative of the most recent 30-yr climatological mean, was utilized to calculate mean monthly temperatures from the time-of-observation-corrected data. These monthly temperature data were subsequently used in Eq. (4) to calculate the start and end dates of the SAS. Grid files with 10-km spacing were created for the onset and end dates using an inverse-distance-squared kriging technique with Surfer proprietary mapping software (Golden Software, Inc., version 6.01), which represents a standard method routinely used by the Minnesota State Climatology Office. Contoured maps were generated from the grid files to display graphically the SAS onset and end dates, denoted by day of the year.

Wind-defined potential snow transport (Qupot) was calculated using Eq. (1). To maximize the spatial resolution for this calculation, wind data were obtained from 86 Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) stations located throughout Minnesota and surrounding areas (Fig. 1). All wind instrumentation at these observing sites is standardized and is mounted at a height of 10 m; direction is reported to the nearest 10°. Wind speed data represent an instantaneous measurement taken either hourly or 3 times per hour for the period of 1996–2001. Wind rose parameters of wind speed class frequency and direction compared favorably to those of a previous study by Baker (1983), which utilized first-order station data records of longer duration (10 yr) in Minnesota. The shorter-duration dataset from ASOS and AWOS observations was consequently judged to be adequate for this study because it captured the inherent daily, seasonal, and annual variability of the wind parameters.

For each location, a wind frequency distribution was calculated from the hourly or subhourly observations. The start and end dates of the SAS were determined for each ASOS and AWOS location by linear mathematical interpolation from the onset- and end-date grid files. Wind data within the starting and ending dates of the SAS for each station were included in the snow transport analysis. A mean threshold for snow transport of 7 m s^{-1} (Tabler 1994) was applied in Eq. (1) such that wind speeds of less than this value were not utilized. For plotting purposes, the 36 reported directions were translated into the 16 cardinal directions by using a weighting factor, and a wind rose plot was generated for each station. To simplify the results presented here, wind data from stations within each of the nine climate divisions (see Fig. 1) were averaged, with 6–11 stations per division. Four observing sites located along the north shore of Lake Superior were treated as one group, separate from the remaining stations in northeast Minnesota (division 3).

Mean snowfall and snowfall density data for use in Tabler's conceptual model [Eq. (3)] were detemined from monthly snowfall totals for cooperative observing stations throughout Minnesota. The SAS-defined snowfall was calculated for each year for the 1971/72–2000/01 seasons. The onset and end dates of the SAS for all snowfall observation locations were determined by linear mathematical interpolation from the grid files. For the beginning and ending SAS months, the fraction of days in the month included in the SAS was multiplied by the total monthly snowfall. The 30-yr (1971–2000) mean snowfall was then computed from the SAS-defined snowfall totals. Snowfall density was calculated as the ratio of liquid precipitation (cm) to snowfall (cm) for all daily values from November to March. Though snow density can vary, both during a storm and afterward following the settling of the deposited snow, the approach taken for assessing snow transport in this study assumes that the density variation based on daily observations is an adequate characterization. Rainfall events and those of mixed precipitation type were not included. Daily snowfall and precipitation data (Summary of the Day, National Climatic Data Center) for 180 cooperative observing locations in Minnesota were utilized. Monthly averages for the 1971–2000 period of record were combined to produce a November–March mean snowfall water equivalent.

Snow-defined potential snow transport Qspot was calculated from the mean snowfall water equivalent data. All units of snow transport were converted from kilograms per meter to metric tons per meter for comparison with other research in existing literature (1000 kg m^{-1} = 1 t m^{-1}). The snow-defined potential snow tranport, along with the wind-defined potential snow transport (Qupot), calculated using Eq. (1), was ratioed to determine the snow relocation coefficient θ.

4. Results and discussion

a. Snow accumulation season

The start date of the SAS varies geographically from 30 October for the northern tier of Minnesota to 17 November along the southeastern border, and the SAS end date shows analogous geographic variability (Figs. 2a,b). Extreme northern areas of Minnesota end the snow accumulation season as late as 4 April, whereas the southern corners end the season almost 3 weeks earlier (13 March). This spread gives an SAS length of approximately 158 and 113 days in the northern and southern portions of the state, respectively.

Because the SAS is a temperature-derived parameter, there are significant topographic features that influence the length of the season. The southwestern corner of Minnesota rises approximately 180 m above the surrounding topography and is called the Buffalo Ridge (or Coteau Des Prairies). At a higher elevation there is a slightly longer season than for surrounding areas (4 days). In addition, there is an area of abrupt elevation change of over 400 m in the northeast, along the north shore of Lake Superior. The SAS onset- and end-date isopleths parallel the shoreline, with a longer season inland because of lower average temperatures. A subtle feature in the SAS length is the shorter season for the Red River Valley along the state's northwestern border. The onset- and end-date contours dip southward east of the valley, corresponding to the elevation change for the Alexandria moraine, which averages 60 m above the valley. The SAS length is a bit shorter for the Minneapolis–Saint Paul metropolitan area than surrounding areas of the same elevation, which could be attributed to the large urban environment resulting in higher mean temperatures.

b. Snowfall statistics

Mean seasonal snowfall totals range from less than 80 cm in southwestern Minnesota to over 140 cm in the northeast, with a gradual increase in total snowfall from west to east (Fig. 3). The high seasonal snowfall for the northeast region can be attributed to the proximity to Lake Superior and the occurrence of lake- and orographically enhanced snow events. The station density in this region is relatively low, which is the probable cause of the inhomogeneous contour pattern.

Recall that snowfall totals presented in Fig. 3 are

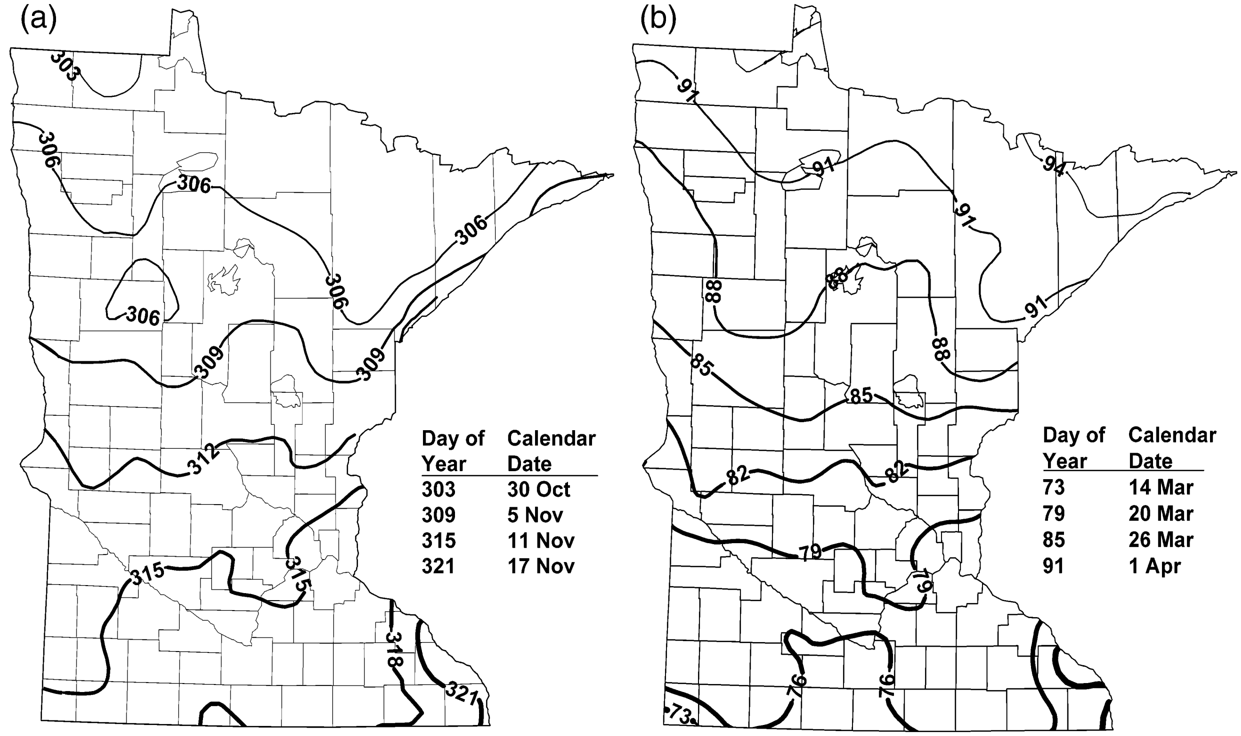

FIG. 2. SAS (a) onset date (day of year) and (b) end date (day of year).

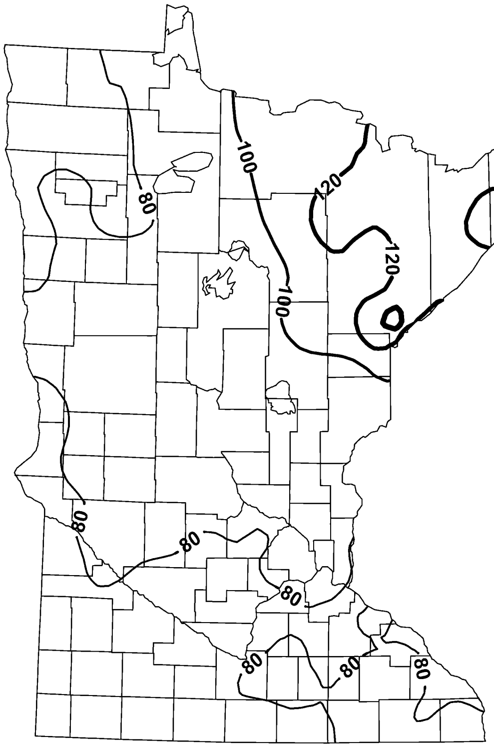

FIG. 3. Mean (1971–2000) snowfall over the SAS (cm).

bounded by the dates of the snow accumulation season. Snow events that occur early in autumn and late in spring can be of significant magnitude; however, they are excluded when utilizing this temperature-based algorithm for defining the snow-drifting season. The difference in annual (July–June) and SAS snowfall is on the order of 20–40 cm and is greatest along Minnesota's northern border. However, snow cover from these events is generally short lived, and the contribution to the total seasonal snow transport is considered to be negligible.

The density of freshly fallen snow in Minnesota exhibits geographic variability in which the northern third of the state experiences a greater frequency of lower-density (70–90 kg m^{-3}) snow events while higher-density (90–110 kg m^{-3}) snow events are more frequent for the southern two-thirds (Fig. 4). Snowfall density also shows a seasonal variation, with a greater frequency of higher-density snow events ($\sim$115 kg m^{-3}) in November and March and lower-density snow events ($\sim$86 kg m^{-3}) occurring in the months of December, January, and February. These observations are comparable to snowfall densities found by Judson and Doesken (2000). For six locations in the central Rocky Mountains, their study finds average density over 4 yr of daily observations in the range of 72–103 kg m^{-3}.

Temporal and spatial variability of snowfall density in Minnesota are attributed to climatological features resulting from temperature variability and the position of the polar jet stream, which strongly influences the track of midlatitude cyclones. Temperature effects are

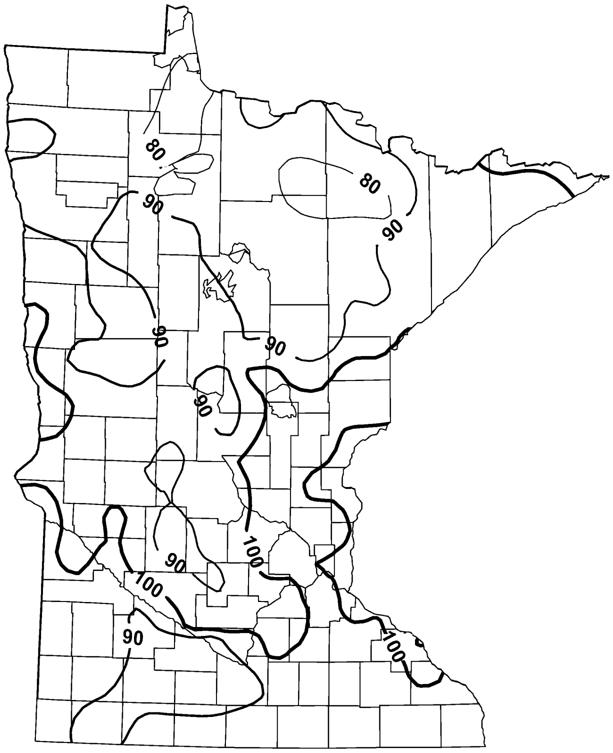

FIG. 4. Mean (1971–2000) snowfall density (kg m^{-3}) for Nov–Mar.

evident for the mean monthly snowfall density and are most pronounced in November and March; January shows the least geographic variability. Snow events that occur early and late in the winter season are more likely to result from storm systems supplied with low-level moisture advection from the Gulf of Mexico. However, by December and January the polar jet has generally migrated south of this area such that it is under the influence of a cold, continental air mass, resulting in a higher frequency of drier snowfalls. The mean January snowfall density exemplifies this pattern, with modest spatial variability and lower densities statewide.

c. Wind frequency distribution

For much of the state, the wind frequency distributions over the snow accumulation season show a strong bimodal distribution in the ranges from 280° to 350° (WNW–NNW) and from 100° to 170° (ESE–SSE), with the former an average of 40% higher than the latter (Figs. 5a–j). Wind direction distributions from stations located near the Lake Superior shore (Fig. 5d) show a more variable distribution, with peaks for the west-northwest and southwest directions. Baker (1983) found similar frequency distributions for the eight first-order National Weather Service observation sites in Minnesota and surrounding areas. His results represent a 10-yr mean of hourly observations taken at airport locations.

The northwest and southeast frequency peaks are attributed to the winter synoptic climatological features for the upper Midwest. The dominant northerly wind vector direction occurs as a result of the position of the polar jet stream, and the east–west components result from the general track of low pressure systems. In contrast to the macroscale characteristics that influence the wind frequency distribution for most locations across Minnesota, microscale processes are evident in the wind regime along the Lake Superior shore. These locations show a seasonally influenced lake–land breeze caused by temperature differences.

The wind data were delimited by wind speed class using categories of less than and equal to or above 7 m s^{-1}. Again, a bimodal distribution is evident for both wind speed categories that is consistent for much of the state (Figs. 5a–c, 5e–j), with the exception of the lakeshore sites (Fig. 5d). Locations along the lake show higher frequencies for all wind directions between south-southwest and north-northwest. The wind rose plots for western (Figs. 5a,e,h) and south-central (Fig. 5i) Minnesota show an equal or higher frequency of wind speeds of equal to or greater than 7 m s^{-1} as compared with frequencies below this threshold. In particular, for extreme southwestern Minnesota (Fig. 5h) the frequency of winds at or above 7 m s^{-1} is greater than those of less than this value for the northwest and north-northwest vector directions. These frequency distribution results have implications for the areas of the state with sufficient wind energy to result in a higher frequency of windblown snow events.

The topographic and vegetative characteristics of the landscape probably influence wind speed and direction frequencies. Because of the high percentage of land used for crop production in the west and south, the winter landscape consists of agricultural fields that are either barren or have a fraction of crop residue cover. This condition results in a low surface roughness. In addition, the topography of this area is relatively flat, with few significant relief changes. These factors reduce the drag force exerted by the surface on the wind and result in an increased frequency of higher wind speeds with a relatively low downward flux of momentum. In contrast, landscape features of north-central and northeastern Minnesota are very different. Hardwood and conifer forests dominate this area, and the topography is also more variable, yielding a much higher surface roughness and an increase in drag force. Therefore, in contrast to western and southern Minnesota, wind speeds are generally lower and the directional component is more variable.

d. Snow transport

Western and southern portions of Minnesota show higher wind-defined potential snow transport totals (40–90 t m^{-1}) than do eastern regions (10–30 t m^{-1}), as calculated from Eq. (1) (Fig. 6a). For much of eastern Minnesota, the frequency of winds above the average transport threshold (7 m s^{-1}) is low, resulting in considerably lower potential snow transport but higher seasonal snowfall totals. Therefore, assuming an unlimited snow supply, wind conditions are such that up to 3 times as much snow can be transported in the west and south as in the northeast.

Tabler (1997) reports a wind-defined potential snow transport for Sioux Falls, South Dakota, of 49 t m^{-1} using wind records for a 5-yr period. The same study also shows a snow transport of 71 t m^{-1} for a location in south-central Minnesota for the 1996/97 season. These values are in close agreement with the calculated snow transport values in this study using wind data from 1996 to 2001. At Prudhoe Bay, Alaska, Tabler et al. (1990) show a snow transport of 268 t m^{-1} using wind records for a 22-yr period, which is an order of magnitude greater than that found for Minnesota. However, in an arctic coastal plain environment, a high percentage of the total observed wind speeds are above the snow transport threshold, as opposed to 20% of the total observations for locations in Minnesota.

The potential snow transport was also calculated based on snowfall and snow density data using Eq. (5), assuming an infinite fetch distance (Qspot). Using this conceptual model, snow transport is in the range of 90–115 and 115–175 t m^{-1} for the western and eastern halves of Minnesota, respectively (Fig. 6b). These results of snow transport as determined by snowfall (Qspot) show geographic variability that is the reverse of that determined by wind (Qupot). Because Qspot is calculated from snowfall statistics, areas of Minnesota with higher seasonal snowfall totals are those with greater snowfall-defined potential snow transport. Therefore, eastern sections of the state, in particular the northeast, experience the highest Qspot totals. With lower snowfall totals in the west, this area shows correspondingly lower snowfall-defined potential snow transport. The magnitude of Qspot for eastern regions of the state is 2 times or more that of Qupot. In these locations where Qspot $>$ Qupot, wind is the primary factor limiting snow transport. However, notice that in an area with high frequencies of winds above 7 m s^{-1} (extreme southwest Minnesota), Qupot is greater than Qspot. In this location, snowfall rather than wind is the factor limiting snow transport, based on these empirical equations. Recall that snowfall totals in this area are 60–70 cm (Fig. 3).

The snow relocation coefficient θ, as determined by the ratio of Qupot and Qspot, is shown in Fig. 7. The landscape and vegetation characteristics of western and southern Minnesota result in an area that transports snow efficiently, unlike northern and eastern areas of the state. Even though the total seasonal snowfall for western and southern Minnesota is relatively low (Fig. 3), there is sufficient wind energy to transport a considerable amount. In converse, snowfall totals are high in the northeast, but the wind is not of sufficient magnitude and transports only 10%–20% of the total potential. The relocation coefficient is necessary for an accurate estimation of the total seasonal snow transport as determined from Tabler's (1994) conceptual model [Eq. (3)]. This simple algorithm incorporates local climatological (wind, snowfall, and snow density) and landscape (fetch distance) characteristics, along with the relocation coefficient, to quantify seasonal snow transport. For local transportation authorities, these results are imperative to design site-specific snow-control techniques properly along problem areas of roadways.

5. Summary and conclusions

The dates of the snow accumulation season exhibit variability as determined by latitude and elevation. Because a temperature-based algorithm defines the SAS, lower average air temperatures result in a longer season that begins earlier in the autumn and persists later into the spring. There is a difference in the annual (July–June) and SAS-defined snowfall of approximately 30 cm; however, snow events contributing to this discrepancy occur early and/or late in the season, and the snow from these events will likely not persist through the winter season. Moreover, for purposes of snow control it is not necessary to include short-lived early- or late-season snow events when computing the total seasonal snow transport.

The location of Minnesota in relation to the position and seasonal migration of the polar jet and the track of midlatitude cyclones are the dominant factors that influence the surface wind regime. Over the snow accumulation season, the wind frequency distribution mode is from a north-to-northwest vector direction, with a second mode from the south-southeast. The importance of topographic and vegetative landscape characteristics is also evident in wind direction and wind speed frequency distributions. In areas with low-growing vegetation and relatively flat topography such as western and south-central Minnesota, the wind direction shows a strong bimodal distribution (northwest and south-southeast). However, the greater relief variability and prominent vegetation that are characteristic of the northeast lead to peak distributions that are weaker than those for western and southern Minnesota.

Locations in western and southern Minnesota experience a high frequency of wind speeds that are equal to or greater than 7 m s^{-1} (the mean snow transport threshold used in this study), whereas northern and eastern regions show much greater frequencies of lower wind speeds. In areas with a low occurrence of higher wind speeds but high seasonal snowfall, there is an order-of-magnitude difference in wind-defined (Qupot) and snowfall-defined (Qspot) potential snow transport, the latter being much greater. However, snowfall totals in western and southern Minnesota are considerably lower than in the east, but prevailing wind speeds are much higher. In this case, both methods of determining potential snow transport (Qupot and Qspot) produce similar results. The implications of this result are sig-

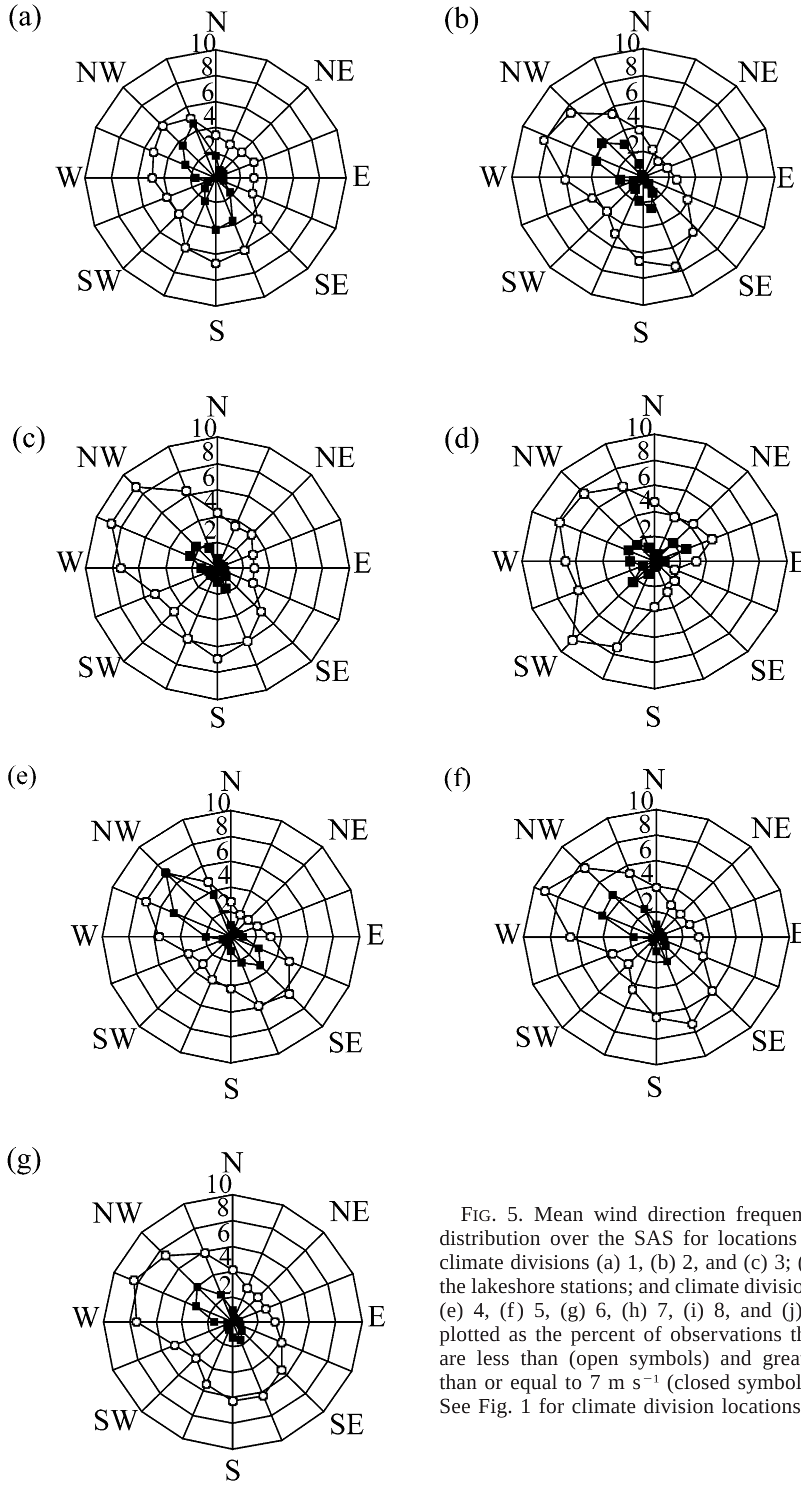

FIG. 5. Mean wind direction frequency distribution over the SAS for locations in climate divisions (a) 1, (b) 2, and (c) 3; (d) the lakeshore stations; and climate divisions (e) 4, (f) 5, (g) 6, (h) 7, (i) 8, and (j) 9 plotted as the percent of observations that are less than (open symbols) and greater than or equal to 7 m s^{-1} (closed symbols). See Fig. 1 for climate division locations.

nificant in regard to the geographic variability in the snowfall relocation coefficient and consequent allocation of snow control resources.

This research illustrates the significance of wind speed frequency distribution for determining the relocation coefficient, which represents a site-specific parameter that is critical for the proper design of snow control measures: in particular, snow fences. Also, investigating wind observations with the spatial distribution in this study demonstrates the importance of landscape characteristics as a key element influencing snow transport. Results from this study have allowed

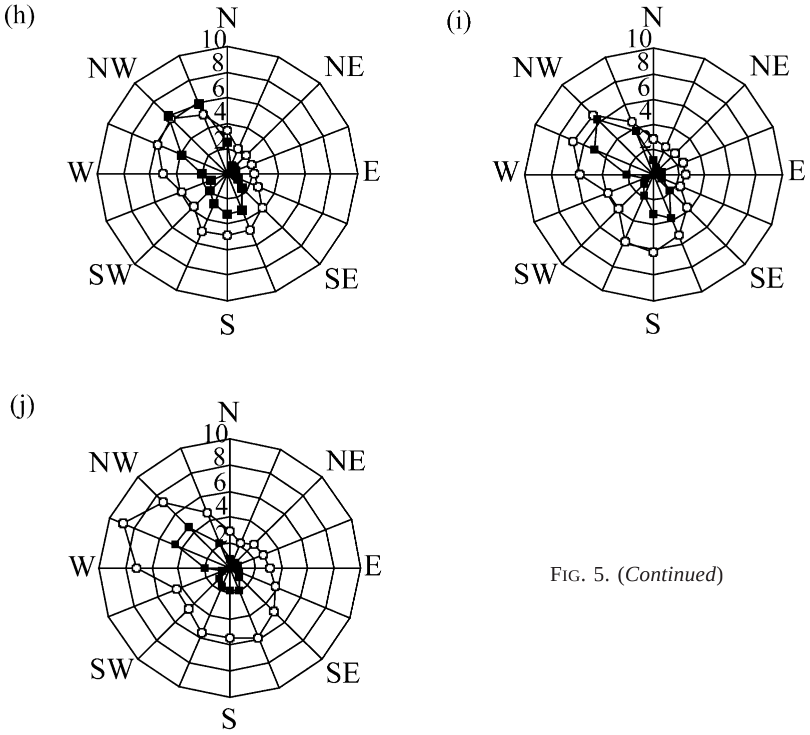

FIG. 5. (*Continued*)

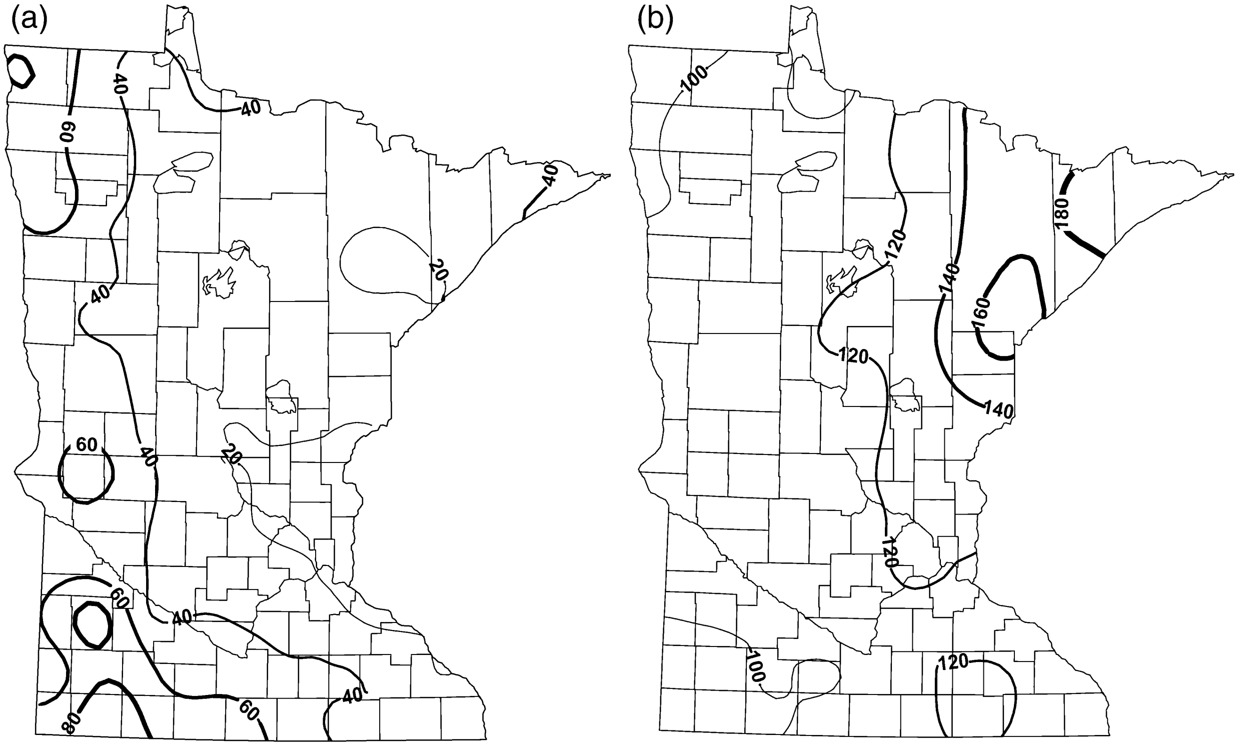

FIG. 6. (a) Wind-defined potential snow transport Qupot (t m^{-1}), and (b) snowfall-defined potential snow transport Qspot (t m^{-1}).

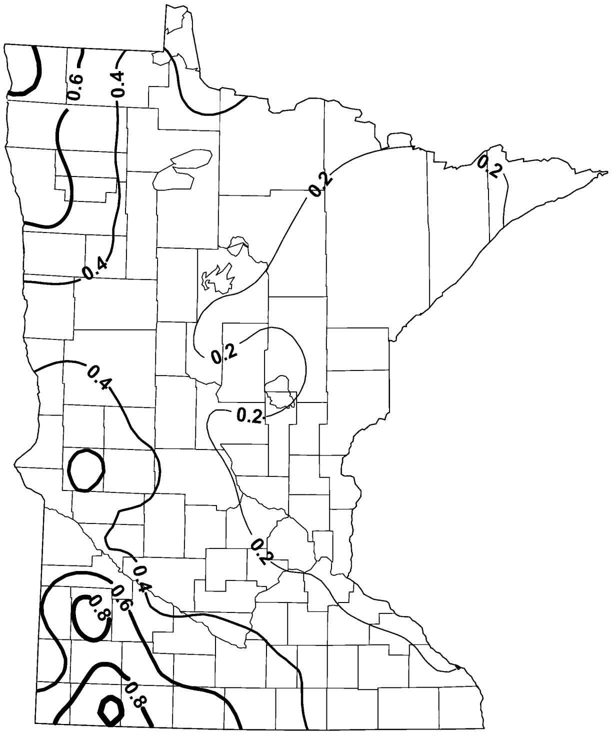

FIG. 7. Snow relocation coefficient (Qupot/Qspot).

for the development of an interactive module (http://www.climate.umn.edu/snow_fence/Components/Design/introduction.htm) that at the time of writing is routinely used by local authorities with the Minnesota Department of Transportation to determine the most effective snow control technique for a given problem area.

Results presented here are based on snow transport models with local climate statistics as input parameters and do not include field validation. Because the models were empirically developed under specific environmental conditions, field studies are necessary to test applicability to Minnesota's landscape characteristics. A case study was conducted by the authors during the winter of 2000/01 to determine snow transport at three living snow-fence sites established at problem locations in southern Minnesota. Snow deposition was determined by following the method of Tabler (1997). Three snow-fence designs were studied over the winter, two eight-row strips of standing corn placed 46 m apart, a twin-row honeysuckle, and single row of alternating honeysuckle and red cedar. Observed snow deposition totals of 30.5, 16.6, and 18.6 t m^{-1} were determined for the corn rows, twin-row honeysuckle, and single row honeysuckle, respectively. Modeled seasonal snow transport totals were calculated by using Eq. (3) and incorporating site-specific climatological and landscape characteristics. The modeled totals were 29.9, 37.7, and 45.1 t m^{-1} for the corn rows, twin-row honeysuckle, and single-row honeysuckle, respectively.

The best agreement between the modeled and observed snow transport was found for the corn-row site, whereas the observed values were approximately one-half of the modeled total for the two other sites. Much of the discrepancy for these sites is attributed to the time in the season at which the fences reached their snow storage capacity. For the two standing corn-row strips, the upwind fence was filled to capacity at the end of the season while the downwind corn-row fence had not yet reached capacity. In contrast, the honeysuckle fences were at their respective snow storage limit more than 2 months before the end of the snow accumulation season. Because there were two sets of corn rows, this allowed for greater snow storage than a single fence row. Although modeled and observed snow transport results were in good agreement for the corn-row site, further research is needed for field validation of the Tabler model. Nevertheless, each site stored a significant amount of snow and protected the respective problem stretch of roadway. More detailed results about the case study could be viewed on the Internet (http://www.climate.umn.edu/snow_fence) as of the time of writing.

Agricultural landscapes in the prairie soil associations of southern and western Minnesota may be problematic for the establishment and maintenance of living snow fences. However, the possibilities of controlling blowing snow with standing rows of field corn left unharvested in autumn present a viable and economic alternative, as mentioned previously. This kind of snow control, in which a ''temporary,'' seasonal solution is favored rather than the commitment and maintenance required to establish a ''permanent'' living snow fence such as shrubbery or pine, is generally seen by local landowners as less obtrusive. These permanent fence types are present, of course, during the growing season and, although research shows an overall positive effect on surrounding crop growth and yield by enhancing the microclimate, take up valuable space and compete with surrounding crops for moisture. These characteristics may cause landowners to view them as an inconvenience, in particular during the critical stage of planting in which too much moisture left over from the winter snowdrift may delay planting and effectively shorten the growing season.

When viewed in a cost–benefit analysis, snow fences, in particular living ones, represent a highly cost effective means of snow control. For much of Minnesota, as well as across the upper Midwest, these fences must be deployed on land used for crop production; therefore, it is in the best interest of local transportation authorities to determine the most suitable placement for snow fences in cooperation with landowners and local community members.

Acknowledgments. This research was supported by a grant from the Minnesota Department of Transportation (Mn/DOT Contract 74708). We are grateful to the following people for their contributions to data analysis and interpretation: Dan Gullickson, Mn/DOT forester;

Kenny Blumenfeld, graduate student in the University of Minnesota Geography Department; Dave Ruschy, information technologist with the University of Minnesota Department of Soil, Water, and Climate; and especially Jim Zandlo, Greg Spoden, and Pete Boulay, climatologists with the Minnesota Department of Natural Resources State Climatology Office.

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