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Sensitivity of snow relocation and sublimation to climate and surface vegetation

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Abstract A physically-based blowing snow model was used to calculate monthly and annual snow transport and sublimation on the Canadian Prairies. Annual erosion of snow from 1 km fallow-fields ranges from 12 to 75% of annual snowfall, more than half of which sublimates before it is transported to the field-edge. Monthly values of blowing snow relocation and sublimation were related to mean monthly climate parameters by simple regression models for stubble and fallow fields. Monthly snow transport and sublimation were found to increase linearly with the most important variable, mean wind speed. Both transport and sublimation increase with decreasing monthly mean temperature. Snow transport increases slightly with increasing humidity because sublimation is suppressed. Both transport and sublimation from fallow-fields increase with increasing snowfall, however over stubble they increase exponentially with increasing depth of snow on the ground for depths equal to or less than the height of vegetation.

INTRODUCTION

The Canadian Prairies possess an open, arid and wind-swept environment of grasslands and extensive grain farms, mixed with wooded areas at the northern and eastern margins. The dry, cool and windy climate produces three distinct features in the ecosystem. The first is the limitation of plant growth by water supply, with water deficits occurring in most years (Richards, 1969). The second is the notable derivation of water supply from the seasonal snow cover, for snowfall provides roughly 40% of annual precipitation and snow melt over 80% of annual runoff (Gray, 1970). The third is the highly-irregular spatial distribution of snow water equivalent at the end of winter because of wind transport, with large accumulations developing in topographic depressions and areas of tall vegetation (woods, shelterbelts, tall grass, brush). Infiltration of snow meltwater to the soils of fields and pastures provides an important replenishment of soil water reserves just before seeding and the spring growth period. In certain years this replenishment has been sufficiently large to provide for successful germination of seeds, even if fall soil moisture has been depleted. The region has a history of vegetation management to promote agricultural productivity, these practises result in a winter land surface that alternates large fields of grain stubble with large fields of bare soil (fallow). There is interest in managing snow cover by modifying land use patterns to enhance the snow retention of agricultural fields and hence promote soil water recharge by meltwater infiltration (de Jong *et al.*, 1986; Nicholaichuk *et al.*, 1986). Because prairie agricultural ecosystems are particularly sensitive to snow water supply and in turn exert a strong control on snow accumulation, the region makes an interesting case study of the sensitivity of snow accumulation processes to winter climate and to vegetation cover.

PRAIRIE BLOWING SNOW MODEL

The Prairie Blowing Snow Model (Pomeroy, 1989) was initially a series of physically-based algorithms for the calculation of snow transport and blowing snow sublimation fluxes at a point, presuming adequate fetch (>500 m) and a complete snow cover. The PBSM fluxes indicate that sublimation losses can be significant but their magnitude is quite sensitive to air temperature and humidity. Transport rate increases with roughly the fourth power of wind speed but sustains a strong sensitivity to land surface roughness (exposed vegetation height and density) and snow cover physical characteristics (cohesion, hardness) (Pomeroy & Gray, 1990; Pomeroy & Male, 1992).

Landine & Gray (1989) demonstrated the application of the PBSM to calculate the disposition of annual snowfall in the Canadian Prairie environment. Pomeroy *et al.* (1993) detail the implementation of the system for this purpose on agricultural terrain where fetch requirements for fully-developed flow are not met and where vegetation and snow depth may be variable. This implementation includes an hourly-based snow mass balance accounting routine which adjusts the hourly fluxes for upwind snow supply, sublimation, snowfall, mid-winter melts and developing-flow conditions on a 100 m resolution scale. The PBSM uses hourly measurements of wind speed, wind direction, air temperature, relative humidity and snowfall occurrence and six-hourly measurements of snow depth and snowfall amount. The validity of snow depth measurements is specific only to their measurement location, hence they are not used to control snow depth in the model, but to index mid-winter melts. Vegetation and land use information are used to determine the land surface inputs for the model: vegetation height, stalk width, stalk density, unobstructed uniform fetch for each wind direction and topographic boundaries. Land surface information is used to assemble a contiguous series of 100 m long "land surface elements", each element having a characteristic vegetative cover and an unobstructed upwind fetch distance. The PBSM sequentially calculates the vertical, horizontal and sublimating snow fluxes "downwind" along a series of land surface elements, with a complete mass balance conducted in each element for each hour.

SIMULATIONS OF BLOWING SNOW FOR THE CANADIAN PRAIRIES

Using hourly meteorological records of the Atmospheric Environment Service (AES), Environment Canada for sixteen climatological stations in the Canadian Prairies, the fully-implemented PBSM provided information on the wind transport and sublimation of snow from grain stubble and fallow surfaces during a six-year period, 1970-1976. These six years represent a range of high and low snowfall years with a mean climate typical of the mean from 1960-1990. The climatological stations represent a range of dominant Prairie landscapes from mixed deciduous forest and farmland (Parklands) in the north to extensive grain-growing regions (wheatlands) in the central and eastern section to short-grass pasture (rangelands) in the south and west. The stations, in the provinces of Alberta, Saskatchewan and Manitoba, are listed along with their mean winter climate (1970-1976) and their vegetative characteristics in Table 1, with locations shown in Fig. 1. The regional climate varies from cool and sub-humid with lower wind speeds and few mid-winter melts in the northeast to warmer and semiarid with higher wind speeds, frequent mid-winter melts and chinooks (Foehn winds) in the southwest.

The hourly fluxes of snow transport, blowing snow sublimation and snow erosion/deposition were compiled from the six years of record to produce mean annual and mean monthly values for blowing snow relocation and sublimation over non-vegetated (fallow) and vegetated (stubble) agricultural fields. An example of the mean annual values for 1 km fields of fallow and stubble from two stations in the Province of Saskatchewan is shown in Fig. 2 where the disposition of snow is divided into that transported off the field by saltation and by suspension, that sublimated in transit and the residual snow that was not eroded. Substantial variation in the mean annual residual snow and the transport

Table 1 Climatological stations and their characteristics.

Station	Vegetative cover	Wind speed[1] (m s^{-1})	Temperature[1] (°C)	Snowfall[2] (mm)
Broadview, Sask.	Wheatlands	4.6	−9.3	123
Calgary, Alta.	Rangelands	5.1	−4.7	122
Coronation, Alta.	Rangelands	4.6	−8.4	169
Dauphin, Man.	Parklands	5.5	−10.0	141
Estevan, Sask.	Wheatlands	6.3	−7.0	107
Medicine Hat, Alta.	Rangelands	4.8	−4.4	113
Moose Jaw, Sask.	Wheatlands	5.8	−7.1	127
North Battleford, Sask.	Parklands	4.5	−9.8	111
Peace River, Alta.	Parklands	3.9	−10.3	155
Portage la Prairie, Man.	Wheatlands	4.9	−8.9	143
Prince Albert, Sask.	Parklands	4.5	−11.6	103
Regina, Sask.	Wheatlands	6.0	−8.9	113
Swift Current, Sask.	Wheatlands	6.6	−6.7	132
Winnipeg, Man.	Wheatlands	5.0	−9.7	106
Wynyard, Sask.	Wheatlands	5.2	−9.9	126
Yorkton, Sask.	Parklands	4.7	−10.6	125

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

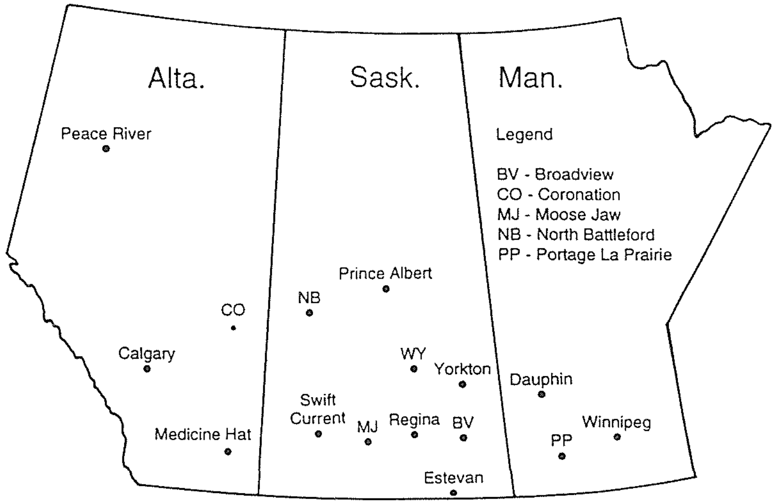

Fig. 1 Location of climatological stations in western Canada.

and sublimation losses occur from station to station. The effect of vegetative cover in limiting the fluxes of blowing snow is well demonstrated by the greater annual losses to saltation, suspension and sublimation from fallow as opposed to stubble vegetative cover. The annual losses to snow transport and sublimation are reduced by up to one-third by the presence of a 25 cm tall stubble. Greater relative reduction in losses occur in high wind speed environments such as Regina. Over the Prairie region, mean annual

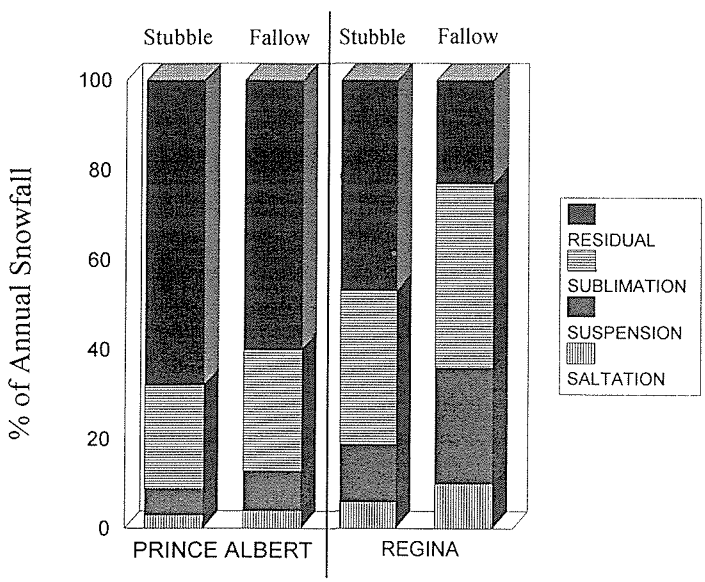

Fig. 2 Disposition of annual snowfall on fields of fallow and stubble vegetation at two stations in western Canada. Residual snow is that not eroded by the wind, the other classes refer to the mode of transport to the field-edge or to sublimation in transit.

erosion of snow from 1 km fallow-fields ranges from 12 to 75% of annual snowfall, of this eroded snow, typically more than one-half sublimates before being transported to the field-edge.

MONTHLY DISPOSITION OF SNOW

To examine the sensitivity of snow redistribution to seasonal and local climate variations, monthly values of blowing snow relocation and sublimation were calculated for stubble and fallow land cover at each of the climate stations and averaged over six years to produce monthly means. These monthly means were then related to mean monthly climate parameters by simple multiple-variable regression models. The regression equations were developed by trial and error with the objectives of maximizing explanation, maintaining simplicity of expression and using mutually-independent climate parameters. The climate parameters are based upon readily-available measurements from AES stations, where temperature and relative humidity are measured at a 2 m height, wind speed and direction are measured at a 10 m height, snowfall water equivalent is measured by a Nipher precipitation gauge and snow cover depth is measured with a ruler.

The parameters used and their ranges are shown in Table 2. The ranges are sufficiently wide to examine the sensitivity of blowing snow transport and sublimation to wind speed, temperature, humidity and snow supply. However, the measurements are all derived from the Canadian Prairie environment and the apparent relationships may depend substantially upon characteristic synoptic and seasonal weather patterns in this region. Application of the equations to conditions outside of the development ranges is not recommended, as the simple linear models used for most variables have not been tested in environments other than that of the Canadian Prairies.

The best-fit regression equations for monthly snow transport (saltation and suspension), TRAN(h) and sublimation, SUB(h) were developed for two vegetation heights, h = 0 cm (fallow field) and h = 25 cm (stubble field), presuming a stalk density of 720 stalks/m^2 and a stalk diameter of 3 mm. These conditions represent two common agricultural field conditions on the Canadian Prairies. The monthly snow transport and sublimation losses, expressed as an average depth of snow water (mm) over a

Table 2 Ranges of climate parameters used in regression development.

Parameter	Range
Mean monthly wind speed	3.6 to 7.1 m s^{-1}
Mean monthly snowfall	6 to 36 mm SWE
Mean monthly snow depth	0.7 to 40.1 cm
Monthly mean of daily maximum air temperature	−15.1 to 11.4°C
Monthly mean of daily minimum air temperature	−26.5 to −0.6°C
Monthly mean of daily maximum relative humidity	73 to 93%
Monthly mean of daily minimum relative humidity	38 to 75%

1 km fetch, 1 m in width, are:

Fallow

$$\text{TRAN}(0) = -14.33 + 2.257u_{10} - 0.245T_{\max} + 0.046RH_{\max} + 0.0786P_m \quad (1)$$

correlation coefficient, $r = 0.90$; mean difference (PBSM − regression); $\Delta = 4.7 * 10^{-7}$ mm; and standard deviation of difference, $s_\Delta = 1.19$ mm.

$$\text{SUB}(0) = 7.206 + 1.764u_{10} - 0.158T_{\max} - 0.176RH_{\max} + 0.191P_m \quad (2)$$

correlation coefficient, $r = 0.80$; mean difference (PBSM − regression); $\Delta = 2.9 * 10^{-8}$ mm; and standard deviation of difference, $s_\Delta = 1.94$ mm.

Stubble

$$\text{TRAN}(25) = -8.259 + 0.889u_{10} + 5.698\exp[-0.101(T_{\max} + 20)] + 0.041RH_{\max} + 3.318\exp[\frac{-8.716}{d}] \quad (3)$$

correlation coefficient, $r = 0.83$; mean difference (PBSM − regression); $\Delta = -1.4 * 10^{-7}$ mm; and standard deviation of difference, $s_\Delta = 1.13$ mm.

$$\text{SUB}(25) = -6.927 + 1.846u_{10} - 0.171T_{\min} - 0.074RH_{\min} + 0.010P_m + 5.218\exp[\frac{-6.12}{d}] \quad (4)$$

correlation coefficient, $r = 0.83$; mean difference (PBSM − regression); $\Delta = -4.2 * 10^{-7}$ mm; and standard deviation of difference, $s_\Delta = 1.75$ mm.

In equations (1) to (4):

u_{10} = mean monthly wind speed at 10 m height (m s^{-1}),
$T_{\max}$ = monthly mean of daily maximum air temperature (0°C),
$T_{\min}$ = monthly mean of daily minimum air temperature (0°C),
$RH_{\max}$ = monthly mean of daily maximum relative humidity (%),
$RH_{\min}$ = monthly mean of daily minimum relative humidity (%),
P_m = mean monthly snowfall (mm snow water equivalent), and
d = mean monthly depth of snow cover (mm snow water equivalent).

As is indicated by the correlation coefficients, the association between PBSM and regression estimates is reasonably high, with mean differences less than 10^{-7} mm of snow water equivalent and standard deviation of differences less than 2 mm of snow water equivalent.

Snowfall in Canada is normally measured with AES Nipher-shielded snow gauges, which have a slight undercatch during high winds, and an under-measurement due to unrecorded trace snowfall events, hence the monthly snow fluxes derived from snowfall may be underestimated (Goodison, 1978). To provide an evaluation that is not subject to this underestimation, the monthly snow fluxes are divided by monthly snowfall to provide dimensionless transport/snowfall and sublimation/snowfall ratios. Evaluation of the sensitivity of the monthly snow flux/snowfall ratios to climate parameters was conducted for each land cover type; fallow and stubble.

Wind speed

The models assume a linear increase in monthly blowing snow transport and sublimation with increasing wind speed. Figure 3 shows transport/snowfall is moderately sensitive to wind speed. The snow-filled stubble condition is aerodynamically similar to that for fallow and there is little difference in the monthly transport flux between the two. An increase in the mean monthly wind speed from 2 to 10 m s^{-1} causes the monthly snow transport loss to increase four-fold. Figure 4 shows the sensitivity of sublimation/snowfall to wind speed is much higher than was that for transport/snowfall. Sublimation losses increase eight-fold as the mean monthly wind speed increases from 2 to 10 m s^{-1}. This is due to the effects of higher wind speed in increasing the availability of blowing snow for sublimation and increasing the ventilation and hence sublimation rate of blowing snow. The small difference in sublimation between fallow and snow-filled stubble surfaces is attributed to differences in the effects of surface roughness, blowing snow frequency, particle travel distance and ventilation of suspended snow particles.

Temperature

Figures 5 and 6 show the mean monthly snow transport/snowfall and sublimation/snowfall ratios decrease with increasing monthly maximum temperature. These trends are due to the decreasing frequency of blowing snow as temperature increases. Figure 7 plots monthly hours of blowing snow and mean monthly temperature at Regina and Prince Albert. The data show the two variables are inversely related during the winter months, i.e. a larger number of hours of blowing snow occur during the months with low temperatures. Low air temperatures result in snow covers with low cohesion and low transport threshold wind speeds. High air temperatures result in ice-covered or highly cohesive "wet" snow. Wind speeds are higher at Regina than at Prince Albert, hence for a

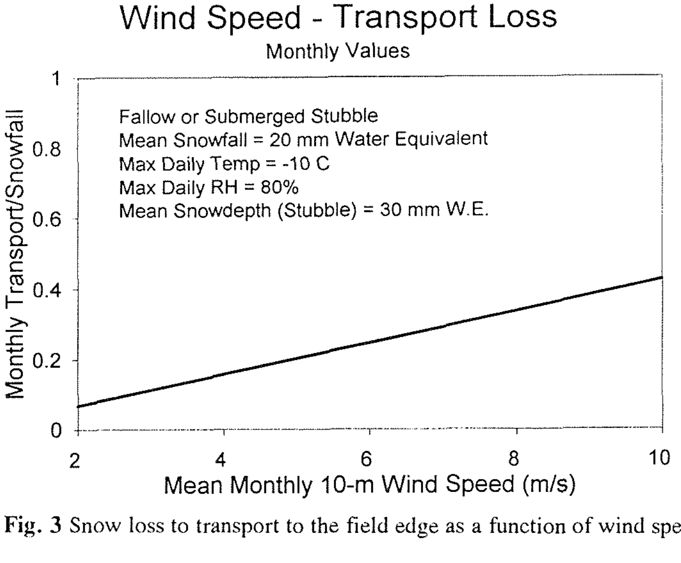

Fig. 3 Snow loss to transport to the field edge as a function of wind speed.

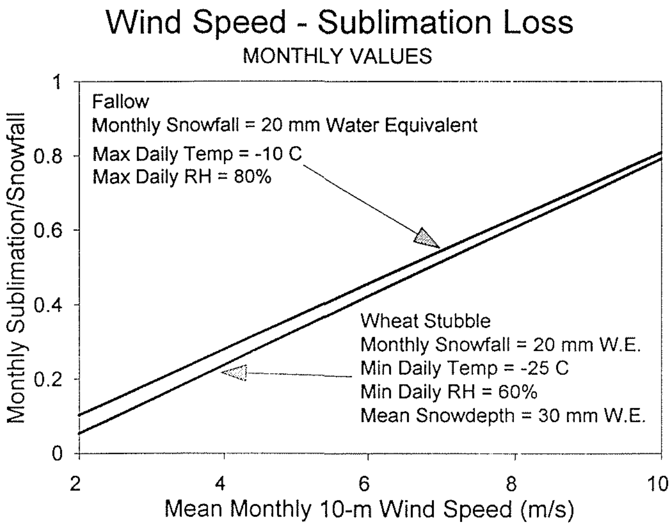

Fig. 4 Snow loss to sublimation in transit as a function of wind speed.

specific air temperature the frequency of blowing snow is higher at Regina.

The effect of decreasing air temperature on snow transport is most important at wind speeds near the transport threshold wind speed. For a mean monthly wind speed of 5 m s^{-1}, transport/snowfall quadruples as the monthly mean of daily maximum air temperature decreases from −2 to −25°C. Mean monthly snow transport on stubble displays a strong temperature dependence due to the effect of mid-season melts in re-exposing buried vegetation. The frequency of these melts increases as temperature increases, hence transport increases dramatically as monthly mean daily maximum temperature drops below −10°C.

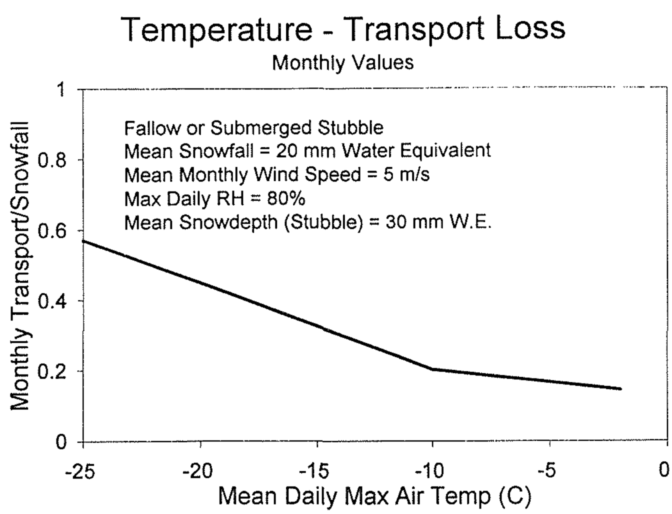

Fig. 5 Snow loss to transport to the field edge as a function of temperature.

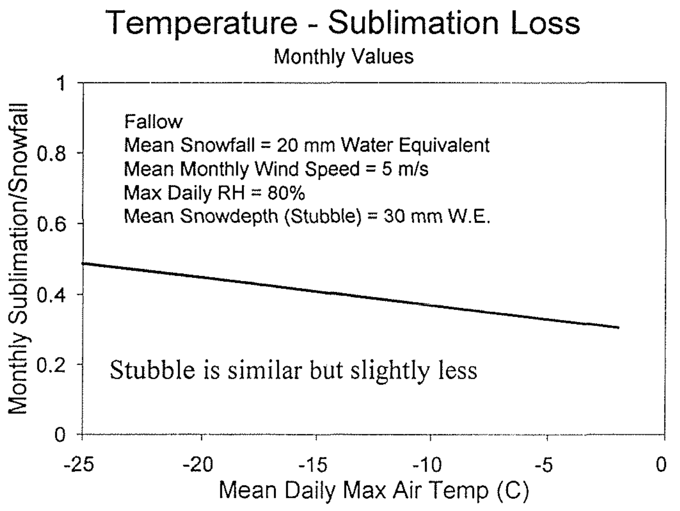

Fig. 6 Snow loss to sublimation in transit as a function of temperature.

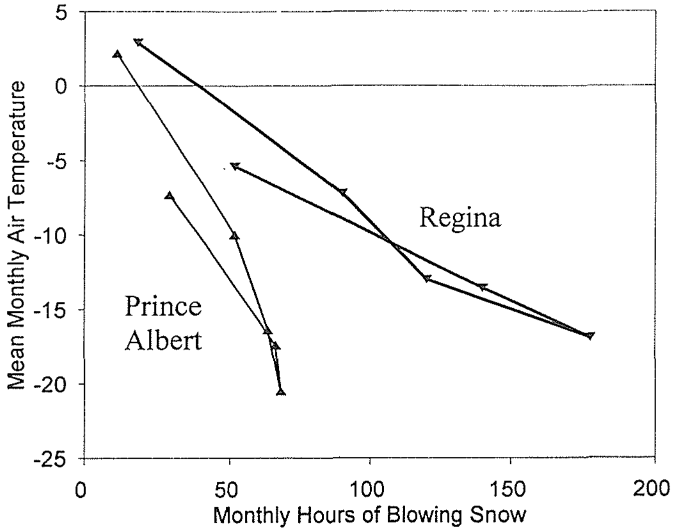

Fig. 7 Mean monthly temperature during the winter season and the monthly hours of blowing snow at Regina and Prince Albert, Saskatchewan.

The variation of monthly sublimation/snowfall with temperature is opposite to the effect of temperature on the instantaneous sublimation rate for an ice sphere. The increased frequency of blowing snow events more than compensates for the lowering of the sublimation rate due to a decrease in temperature. However, the lower sublimation rates dampen the increase in monthly sublimation/snowfall with decreasing temperature. As the maximum air temperature drops from −2 to −25°C, sublimation/snowfall only increases 1.5 fold, far less than the increase in transport/snowfall. The relative insensitivity of monthly sublimation to temperature is supported by the findings of Tabler

(1975) in Wyoming and Benson (1982) in Alaska, who reported sublimation/snowfall ratios of similar magnitude for the two regions.

Relative humidity

Figure 8 shows monthly transport/snowfall on fallow and stubble land increasing slightly with increasing relative humidity. This trend is presumed due to higher humidities that suppress sublimation, leaving more snow available for transport to the field edge. In contrast to transport, Fig. 9 shows monthly sublimation/snowfall decreasing notably

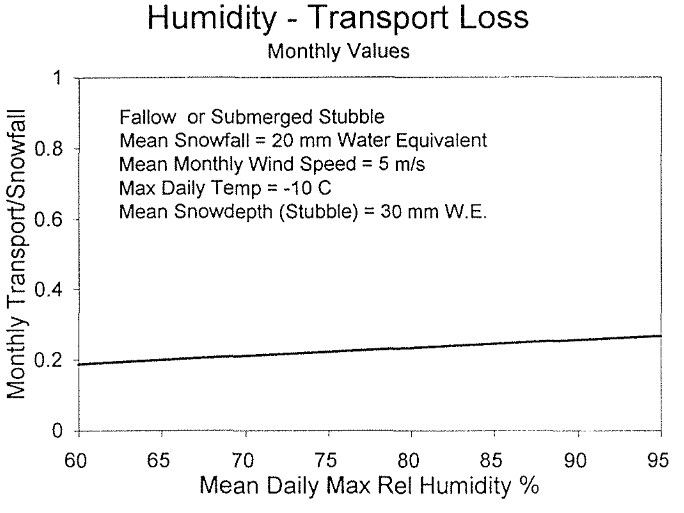

Fig. 8 Snow loss to transport to the field edge as a function of relative humidity.

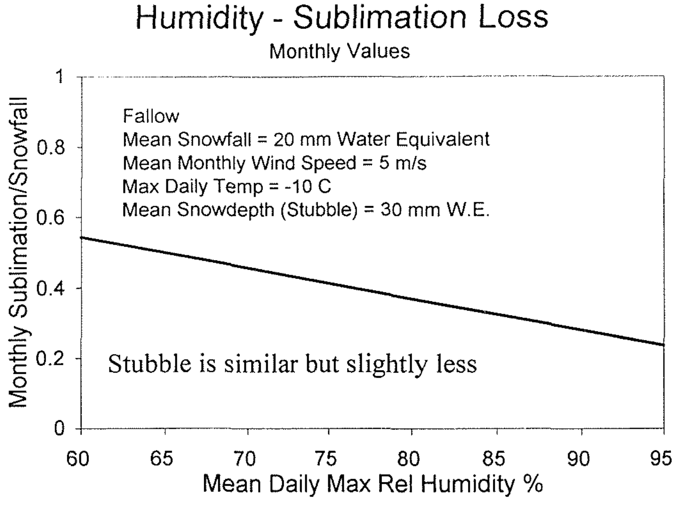

Fig. 9 Snow loss to sublimation in transit as a function of relative humidity.

with increasing relative humidity. An increase in mean daily maximum relative humidity from 60 to 95% results in a decrease in monthly sublimation/snowfall of almost two-fold. This decrease is due to the inverse relationship between instantaneous sublimation rate and relative humidity.

Snowfall and snow depth

Figures 10 and 11 provide examples of the effect of monthly snowfall and snow depth on the monthly transport/snowfall ratio. On fallow land or snow-filled stubble, monthly

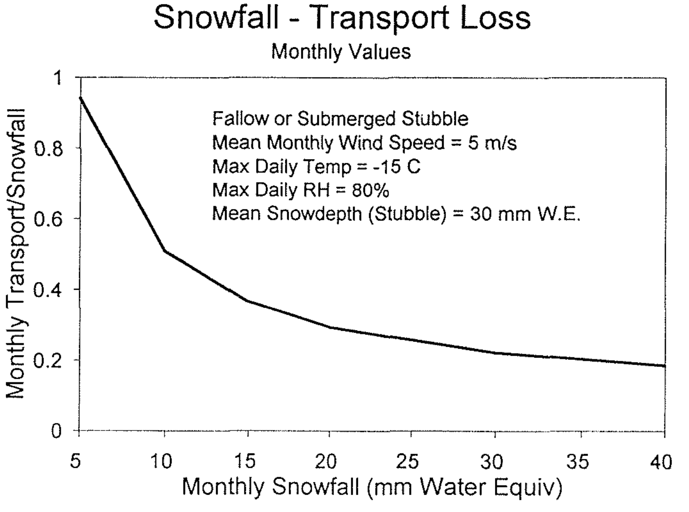

Fig. 10 Snow loss to transport to the field edge as a function of snowfall.

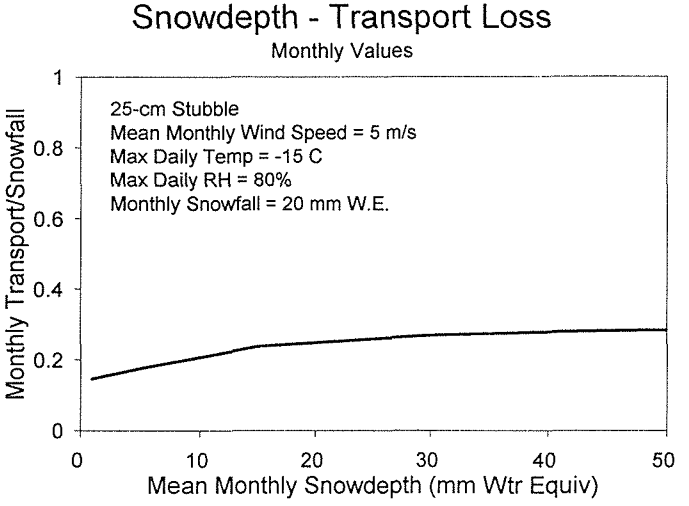

Fig. 11 Snow loss to transport to the field edge as a function of snow depth.

transport/snowfall decreases exponentially with increasing mean monthly snowfall. When monthly snowfall is small (less than 10 mm) much of fallen snow is transported to the edge of a field, even for relatively low mean monthly wind speeds. The rate of decrease in transport/snowfall with increasing snowfall diminishes when sufficient snow is available to sustain transport. For typical prairie mid-winter temperature and humidity (−15°C, 80% relative humidity) and a mean monthly wind speed of 5 m s^{-1}, roughly 20 mm of snowfall per month is sufficient to sustain transport. Higher wind speeds would require more snowfall to sustain the same transport/snowfall ratio. Monthly sublimation/snowfall, though not shown, is normally sustained at lower wind speeds than is transport/snowfall, as the monthly sublimation loss exhibits a greater increase per unit increase in snowfall.

On stubble land, mean monthly snow transport and sublimation increase exponentially with increasing depth of snow. However, the ratios of transport/snowfall and sublimation/snowfall increase only slightly with increasing snow depth because snow depth and snowfall are positively-related. The largest proportional increase in transport and sublimation fluxes with snow depth occurs when the snow cover water equivalent is less than 30 mm. This non-linearity occurs because aerodynamic drag is highly sensitive to the exposed stalk height when stubble stalks are well-exposed to the wind. After snow inundates the vegetation, snow transport is similar to that on a field of fallow.

CONCLUSIONS

Monthly means of wind speed, daily air temperature, daily relative humidity, snowfall and depth of snow cover affect the monthly transport and sublimation of blowing snow. The relationships between these variables and the blowing snow losses depend on the vegetative cover and notably different relationships exist for fallow and wheat-stubble. Regression-based relationships developed from the Canadian Prairie environment provide a means of estimating blowing snow losses at locations with incomplete meteorological data and of defining the sensitivity of blowing snow to climatological factors. Monthly snow transport and sublimation increase linearly with mean wind speed, the most important climate parameter, and to a lesser extent with decreasing monthly mean temperature. Snow transport increases slightly with increasing relative humidity, whereas sublimation decreases notably with increasing relative humidity. Both transport and sublimation from fallow-fields increase with increasing snowfall. On stubble these fluxes increase exponentially with increasing depth of snow on the ground for depths less than or equal to the height of vegetation. Because increasing temperatures increase the blowing snow sublimation rate *but more importantly* decrease the frequency of blowing snow, increases in winter temperature across the prairies of less than 5°C (as anticipated by climate change scenarios) would not significantly affect blowing snow losses unless accompanied by a decrease in snowfall or presence of snow cover or by a change in wind speed regime or vegetative cover. Vegetative cover, wind speed and snowfall, which are less-confidently predicted by climate change scenarios, are more important parameters in estimating the change in blowing snow losses due to changes in climate.

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