Agricultural Controls on Snow Transport and Sublimation Throughout the Canadian Prairies

1. Introduction

1.1 Background

Wind is a controlling factor of snow retention during winter and water management during spring for agriculture in the Canadian Prairies. Winters in the Canadian Prairies are dry, cold, and windy (Nkemdirim, 1996). The Prairies cover a triangular-shaped region spanning the area from southwestern Manitoba to southern Alberta. The region is characterised by relatively flat topography, and most of the region has been converted into croplands for agriculture (Vankosky et al., 2017). The growing season for most crops starts with seeding in April, and the soil must have sufficient moisture at this time for seeds to grow (Champagne et al., 2012). Two major factors that influence soil moisture levels are water from rainfall and water infiltration from snowmelt. Due to variability in the amount of precipitation by rain at the beginning of spring, rainfall alone does not provide consistent sufficient moisture for seeding (Hersbach et al., 2020). The water content of soil from snowmelt depends on the mass of snow at the time when snow starts to melt. Snow depth can be affected by snow blown by wind and mass transfer of snow by sublimation, both of which are influenced by the amount of vegetation in the area (McConkey et al., 1997).

1.2 Snow Transport and Sublimation

Snow transport by wind occurs when the shear stress exerted on a snowpack exceeds the intergranular bonds holding individual snow particles together (Equation 1). The minimum wind speed required to initiate movement of snow is referred to as the transport threshold (Li & Pomeroy, 1997).

$$\tau = K\rho\frac{du}{dz}$$

Equation (1): Equation for shear stress (τ, units: N/m^2), where K = Eddy viscosity (m^2/s), ρ = air density (kg/m^3), u = wind speed (m/s), and z is height above surface (m) (Mellor, 1965)

At a set height z, an increase in wind speed increases the wind speed gradient, increasing the shear stress exerted on the snow, assuming a no-slip condition at the snow surface (Figure 1a). The transport threshold increases as the water content of the snowpack increases, increasing cohesion between particles, requiring a greater wind speed for initial movement (Li & Pomeroy,1997). This is heavily dependent on temperature, with higher temperatures increasing the water content through melting. If the transport threshold is passed, snow particles are displaced and form a saltation layer, where particles are lifted from the surface temporarily before they fall back to the surface of the snowpack. If wind speed is great enough, snow is lifted past the saltation layer and forms a suspension layer, where it continues to be transported in the direction of the wind (Pomeroy, 1989).

Sublimation is characterised by the transfer of snow from the solid state to vapour and occurs at the surface of the snowpack and within the saltation and suspension layers. As wind speed increases, more particles are displaced from the snowpack and become part of the saltation and suspension layers (Pomeroy & Male, 1992). Once removed from the snow surface, a greater surface area of the snow particles is exposed to the air relative to particles in the snowpack. Sublimation rate increases with increased exposure to air, a decrease in relative humidity of the atmosphere, and increasing temperature (Schmidt, 1972).

1.3 Effects of Crop Stubble

The wind-driven shear stress at the snow surface is impacted by vegetation. The presence of vegetation decreases the wind speed gradient at the snow surface (Figure 1), decreasing the amount of stress applied to the top of the snowpack (Equation 1). To reduce losses due to wind-driven snow transportation and sublimation and increase snow retention at the end of the winter season, farmers may choose to leave some vegetation during harvesting at the end of the growing season (stubble) rather than removing all vegetation and tilling the field (fallow; Figure 1). The field is left as stubble at the end of the growing season, lasts through the winter, and increases the amount of snow left to melt and infiltrate the soil at the beginning of next year’s growing season (McConkey et. al, 1992).

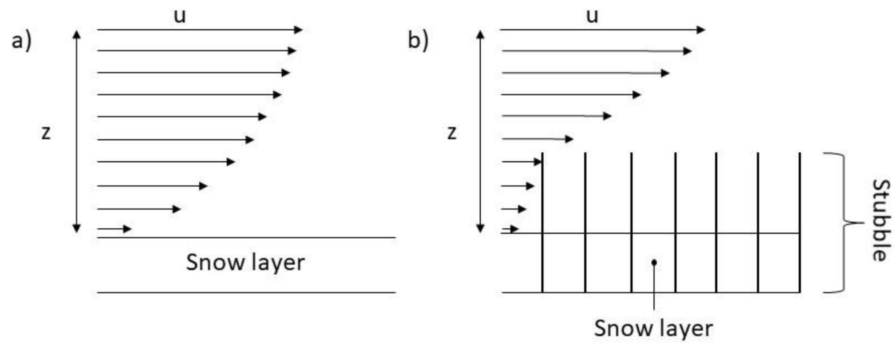

Figure 1) Simplified diagram of the wind speed gradient ($\frac{du}{dz}$) for fallow (a) and stubble (b) conditions, where wind speed is u (m/s) and height above snow surface is z (m).

<u>1.4 Study Goals</u>

The goal of this study is to answer the following questions:

According to Equations (2) - (5):

1) Where in the Canadian Prairies does stubble most reduce snow transport and sublimation during the winter?

2) During which months does stubble most reduce snow transport and sublimation?

3) Where and when do the models produce the most physically sensible results?

2. Methods

<u>2.1 The Model</u>

The models used in this study are a set of regression equations by Pomeroy & Gray (1994) developed to represent a simplified version of the Prairie Blowing Snow Model (PBSM). The PBSM is a physically-based model developed to calculate vertical, horizontal, and sublimating snow fluxes along land surface elements to determine the rate of snow transport and sublimation (Pomeroy & Gray, 1994). The simplified linear models (Equations 2 - 5) calculate the amount of snow (in millimetres of snow water equivalent, or mmSWE) removed from the resting snowpack due to sublimation and transportation by wind in both stubble and fallow conditions. The crop height used for the stubble condition is 25cm above ground, which is equal to 61.8 mmSWE (Appendix, Equation 1).

$$TRAN(0) = -14.33 + 2.257u_{10} - 0.245\,T_{max} + 0.046RH_{max} + 0.0786\,P_{m}$$

$$TRAN(25) = -8.259 + 0.889u_{10} + 5.698e^{[-0.101(T_{max}+20)]} + 0.0417RH_{max} + 3.318e^{[-\frac{8.716}{d}]}$$

$$SUB(0) = 7.206 + 1.764u_{10} - 0.158T_{max} - 0.176RH_{max} + 0.191P_{m}$$

$$SUB(25) = -6.927 + 1.846u_{10} - 0.171T_{min} - 0.074RH_{min} + 0.010P_{m} + 5.218e^{[-\frac{6.12}{d}]}$$

Equations (2) - (5)

TRAN(0) and TRAN(25) are transport out of fallow and stubble fields while SUB(0) and SUB(25) are sublimation out of fallow and stubble fields, respectively. Inputs included are mean monthly wind speed at 10m height (u_{10}, units: m/s), monthly mean of daily maximum and minimum air temperature (T_{max} and T_{min}, units: °C), monthly mean of daily maximum and minimum relative humidity (RH_{max} and RH_{min}, units: %) and mean monthly snowfall and depth of snow cover (P_m and d, units: mmSWE) (Table 1).

2.2 Data

Data for temperature at two metres, dew point temperature at two metres, snow depth, snowfall, and wind speed at 10 metres were downloaded from the ERA5 database for all months from 1979 to 2021 (Hersbach et al., 2020). Relative humidity was calculated using two metre temperature and two metre dew point temperature (ECMWF, 2016), and wind speed was corrected using a bias calculation due to ERA5 underestimations of wind speed in the Prairies (Betts et al., 2019). Average monthly values of snow depth, snowfall, and wind speed were calculated, as well as monthly average maximums and minimums for relative humidity and temperature. Input units, calculations, and ranges can be found in Table 1.

Model Input	Downloaded	Calculation	Range
Snow depth d mmSWE Monthly averages	Snow depth (mSWE) Monthly averages	$mmSWE = 1000mSWE$	0 to 258.0 mmSWE
Snowfall P_m mmSWE Monthly averages	Snowfall (mSWE) Monthly averages	$mmSWE = 1000mSWE$	0 to 106.2 mmSWE
Relative Humidity RH_{max}, RH_{min} % Maximum monthly averages and minimum monthly averages	Two metre temperature, T_{2m} (K) Two metre dew point temperature, T_{d2m} (K) Hourly values	$e_{sat,T} = a_1 e^{a_3(T_{2m} - T_0)/(T_{2m} - a_4)}$ $e_{sat,Td} = a_1 e^{a_3(T_{d2m} - T_0)/(T_{d2m} - a_4)}$ $RH = 100\frac{e_{sat,Td}}{e_{sat,T}}$ a_1 = 611.21 Pa a_3 = 17.502 a_4 = 32.19 K T_0 = 273.16 K	14.8% to 98.5%
Temperature T_{max}, T_{min} °C Maximum monthly averages and minimum monthly averages	Two metre temperature (K) Hourly values	$T(°C) = T(K) - 273.15$	-34.5°C to 18.4°C
Wind speed u_{10} m/s Monthly averages	Wind speed u_{10}' m/s Monthly averages	$Bias = 0.22 - 0.22 * u_{10}'$ $u_{10} = u_{10}' - Bias$	2.1 to 8.7 m/s

Table 1: Units, downloaded data from ERA5 for calculations, calculations, and variable ranges for inputs used in model. While snow depth reaches values higher than 25cm, only values of 25cm or below were used in this study.

Transport and sublimation values were calculated from November to April for each grid cell and each month in mmSWE. Snow depth values of over 61.8 mmSWE were not included in the calculations for transport and sublimation under stubble and fallow conditions, as these values exceed the height of vegetation and the stubble fields no longer have a significant effect on transportation and sublimation compared to fallow fields (Pomeroy & Gray, 1994). Negative output values for transportation and sublimation were set equal to 0 to account for non-physical outcomes. The difference in transportation and sublimation was calculated by subtracting the fallow outcome from the stubble outcome (Equations 6 and 7).

$$\Delta TRAN = TRAN(25) - TRAN(0)$$
$$= 6.071 - 1.368u_{10} + 5.698e^{-0.101(T_{max} + 20)} + 0.245T_{max} - 0.0043RH_{max} + 3.318^{-\frac{8.716}{d}} - 0.0786P_{m}$$

$$\Delta SUB = SUB(25) - SUB(0)$$
$$=- 14.133 + 0.082u_{10} - 0.171T_{min} + 0.158T_{max} - 0.074RH_{min} + 0.176RH_{max} - 0.181P_{m} + 5.218e^{-\frac{6.12}{d}}$$

Equations (6) and (7).

When $\Delta TRAN$ < 0 or ΔSUB < 0, more snow is retained under stubble conditions.

2.3 Calculating Validity

This model was created and tested using inputs from 16 different locations in the Canadian Prairies, and it was recommended to only use the equations within the Prairie region (Pomeroy & Gray, 1994). This study aims to find if the model is indeed applicable to the entire region, and if not, in which areas the equation outputs hold. The model is considered to be invalid when the calculated sublimation and transport differences between stubble and fallow conditions are positive, i.e. when snow lost in fallow conditions is found to be less than snow lost in stubble conditions. It is not physically sensible for stubble conditions to increase the amount of transport and sublimation, as previous studies have consistently mentioned a strong correlation between stubble and an increase in snow retention (Pomeroy & Gray, 1994; McConkey et al., 1997; Campbell et al., 1992). The percentage of physically insensible values per grid cell was calculated by finding the percentage of months when $\Delta TRAN$ >0 and ΔSUB > 0. The most (least) valid locations are taken to be the 10% of grid cells where $\Delta TRAN$ and ΔSUB are most (least) frequently negative.

To compare the conditions in which the model is not physically sensible, the input variables were normalized at each location (Equation 8).

$$N_{norm}(x, y) = \frac{N(x,y) - \bar{N}}{\sigma_{N}}$$

Equation (8) Where N_{norm} is the normalized time-averaged variable, $\bar{N}$ is the variable averaged over space and time, and σ_{N} is the standard deviation of the variable over space and time.

2.4 Calculating spatial effectiveness

Areas where ΔSUB and $\Delta TRAN$ are minimized are the areas that benefit the most from using stubble conditions to retain snow. These areas were determined by taking the average $\Delta TRAN$ and ΔSUB over all time (November to April, 1979-2021) per location and finding the 10% of locations with the smallest values of $\Delta TRAN$ and ΔSUB.

2.5 Calculating temporal effectiveness

To test the impact of stubble in time, average $\Delta TRAN$ and ΔSUB were divided by average snowfall over the entire season to determine which months when transport and sublimation are most reduced by stubble relative to average snowfall. This is done to measure in which months stubble retains the most snow relative to how much snow the area receives over an entire season. $\Delta TRAN$ and ΔSUB were also divided by transport in fallow conditions and sublimation in fallow conditions to find relative change in outgoing flux.

3. **Results**

3.1 Model Validity in Space and Time

The transport model was found to be most valid in southern Alberta and a small portion of southern Saskatchewan, and least valid around the northern border of the Canadian Prairie region (Figure 2). Areas with lowest validity had lower wind speeds, higher relative humidity, lower temperatures, and higher snow depth values than areas with higher validity (Figure 3).

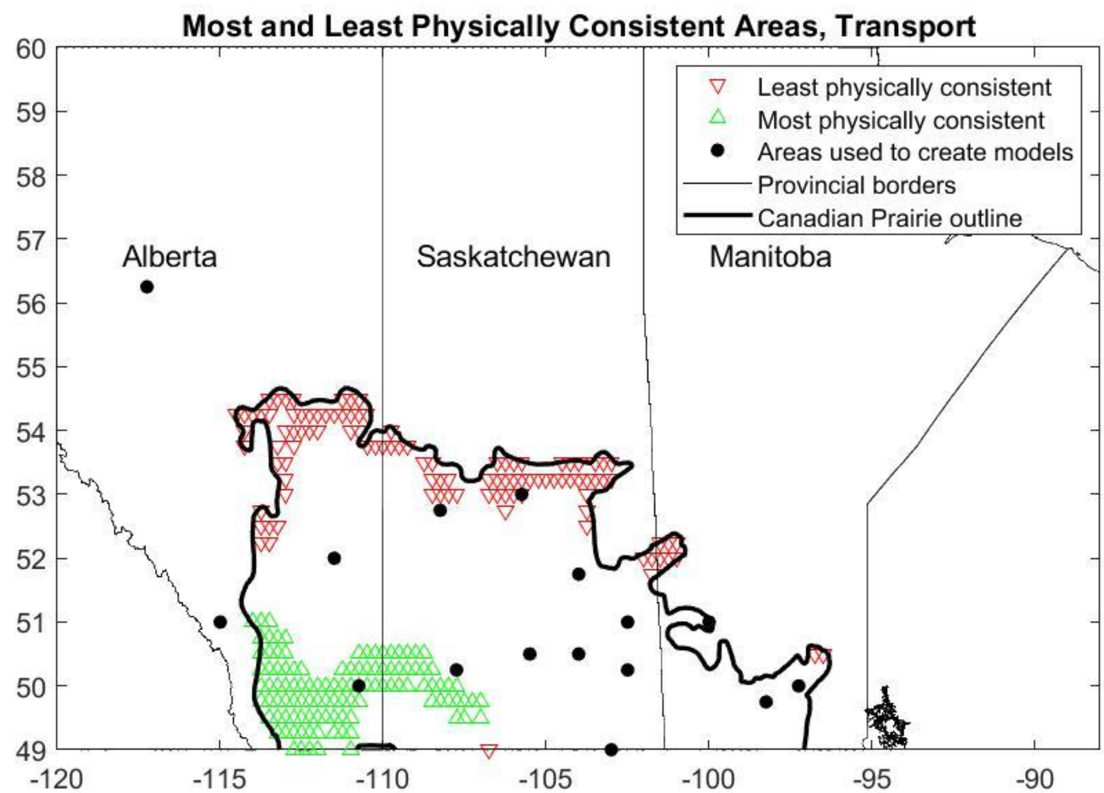

Figure 2) Areas in the Canadian Prairies where the transport model is most and least physically consistent

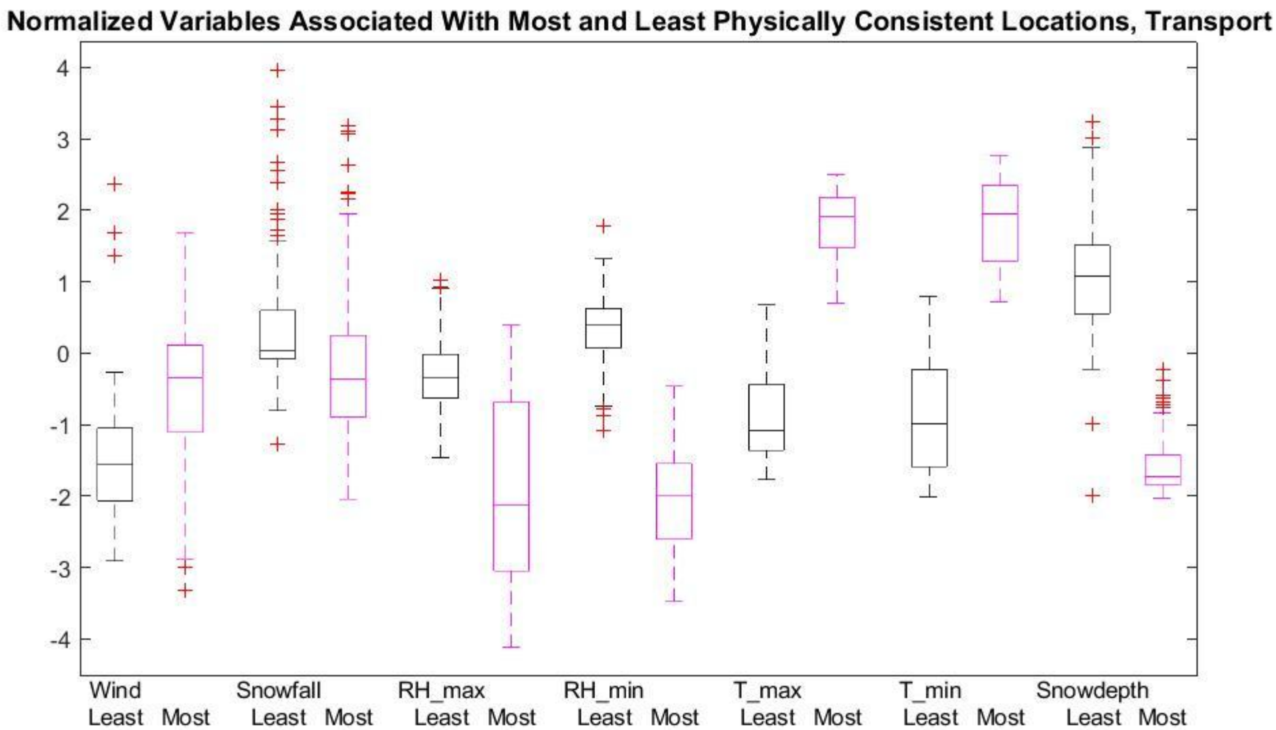

Figure 3) Normalized variation in input variables for most valid and least valid transport model locations.

The sublimation model was most valid in southern Alberta and a small portion of southern Manitoba, while the areas with the lowest validity were found to be in the northern area of the Prairies around the Alberta and Saskatchewan border and a number of locations throughout southern Saskatchewan (Figure 4). These areas had higher wind speed, higher relative humidity, lower temperatures, and higher snow depth than areas with higher sublimation validity (Figure 5).

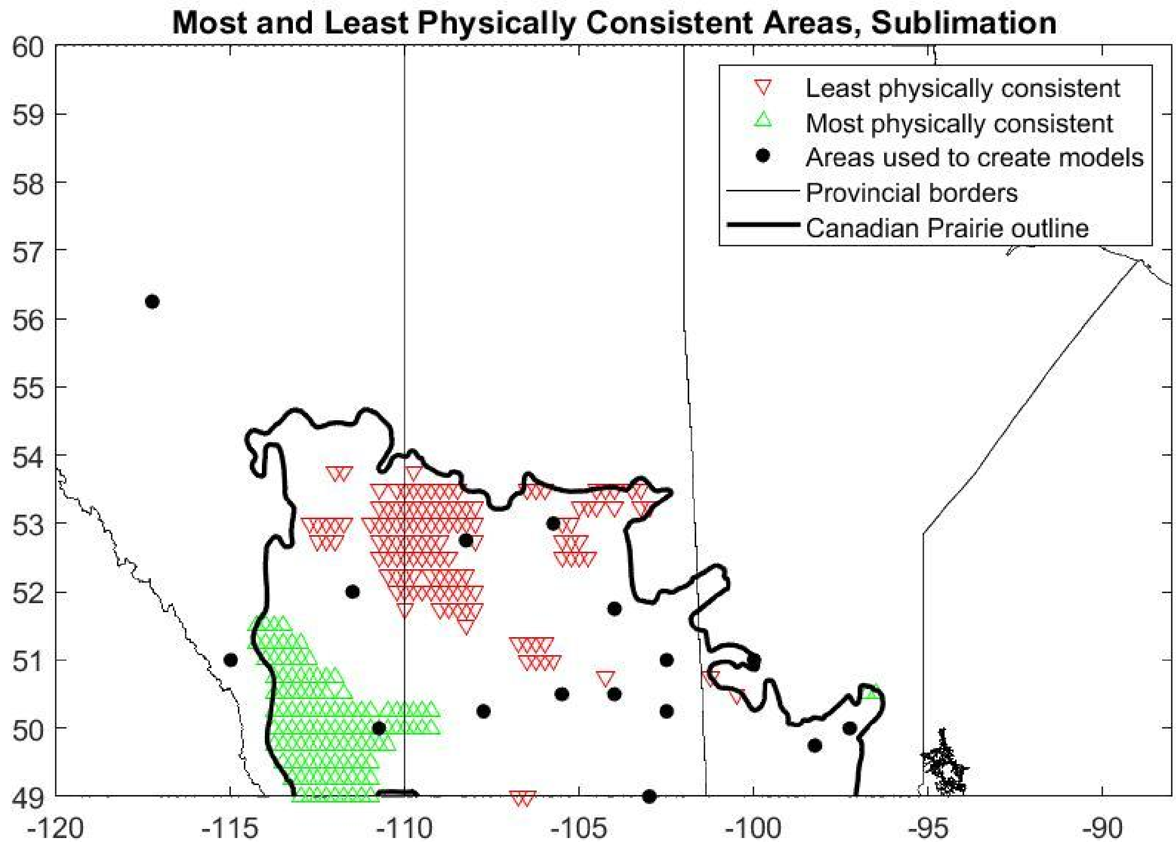

Figure 4) Areas in the Canadian Prairies where the sublimation model is most and least physically consistent.

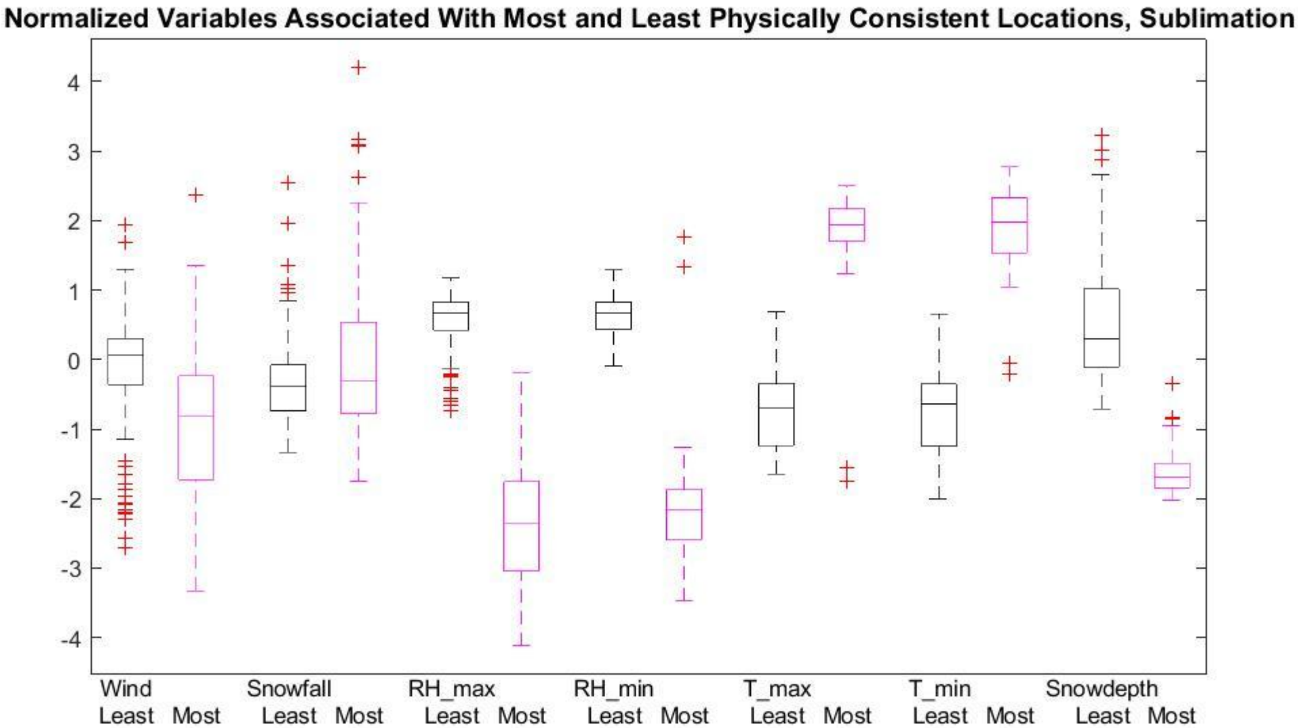

Figure 5) Normalized variation in input variables for most valid and least valid sublimation model locations.

The model was least valid from February to April for transport and sublimation, though there were considerably more positive difference values for the transport model (Figure 6).

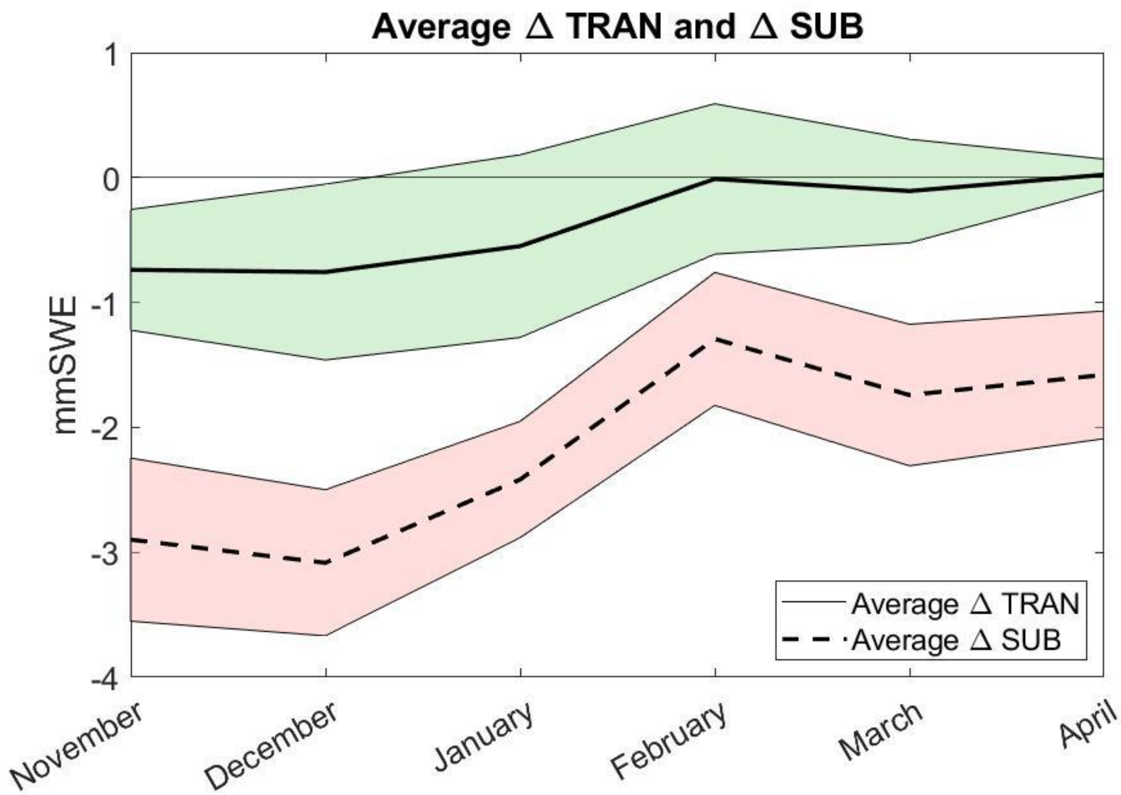

Figure 6) Average monthly $\Delta TRAN$ and ΔSUB over all years and locations. Shaded region represents +/- one standard deviation of the average.

<u>3.2 Areas Benefiting from Stubble Impact</u>

The difference in transport between fallow and stubble conditions was found to be greatest in southern Saskatchewan and some areas along the Canada - United States border (Figure 8). The sublimation difference was greatest in southern Alberta and a few areas in southern Saskatchewan and southern Manitoba (Figure 9).

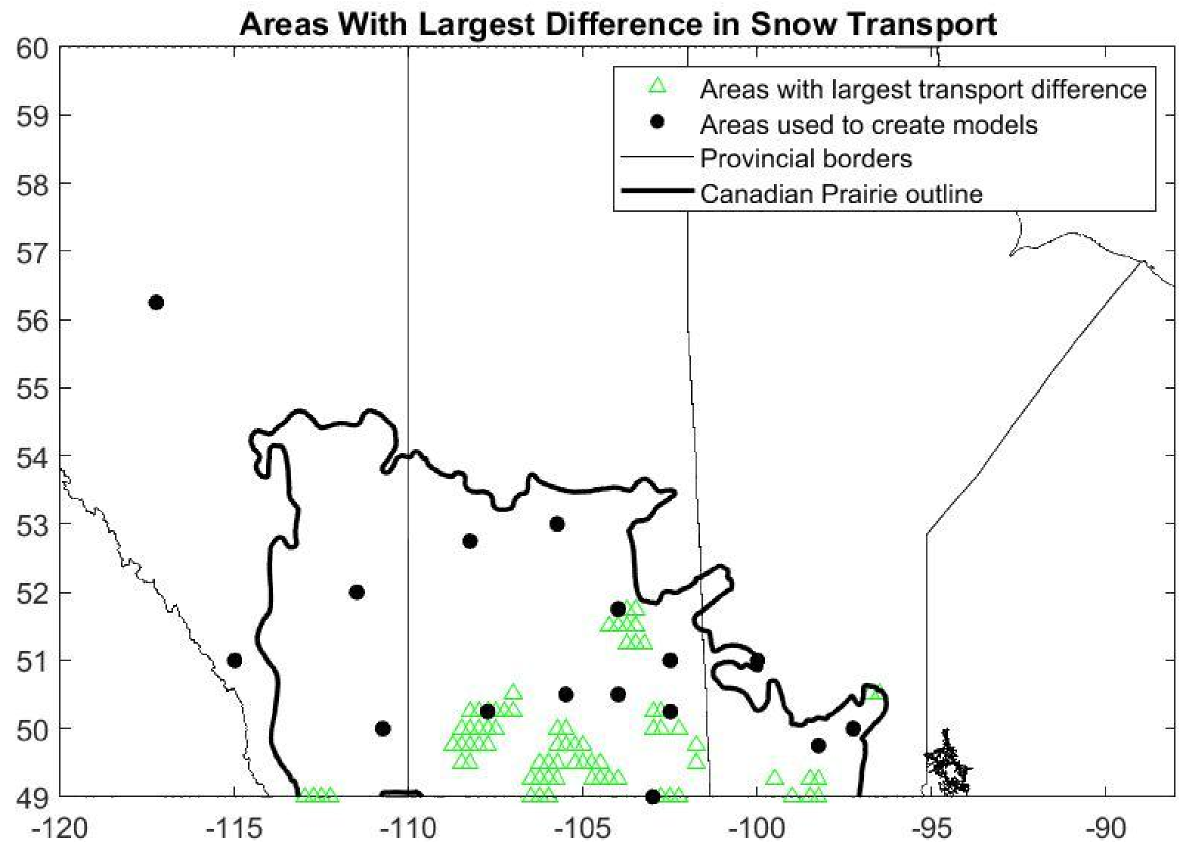

Figure 8) Areas where using stubble conditions is most effective to combat snow loss from transport.

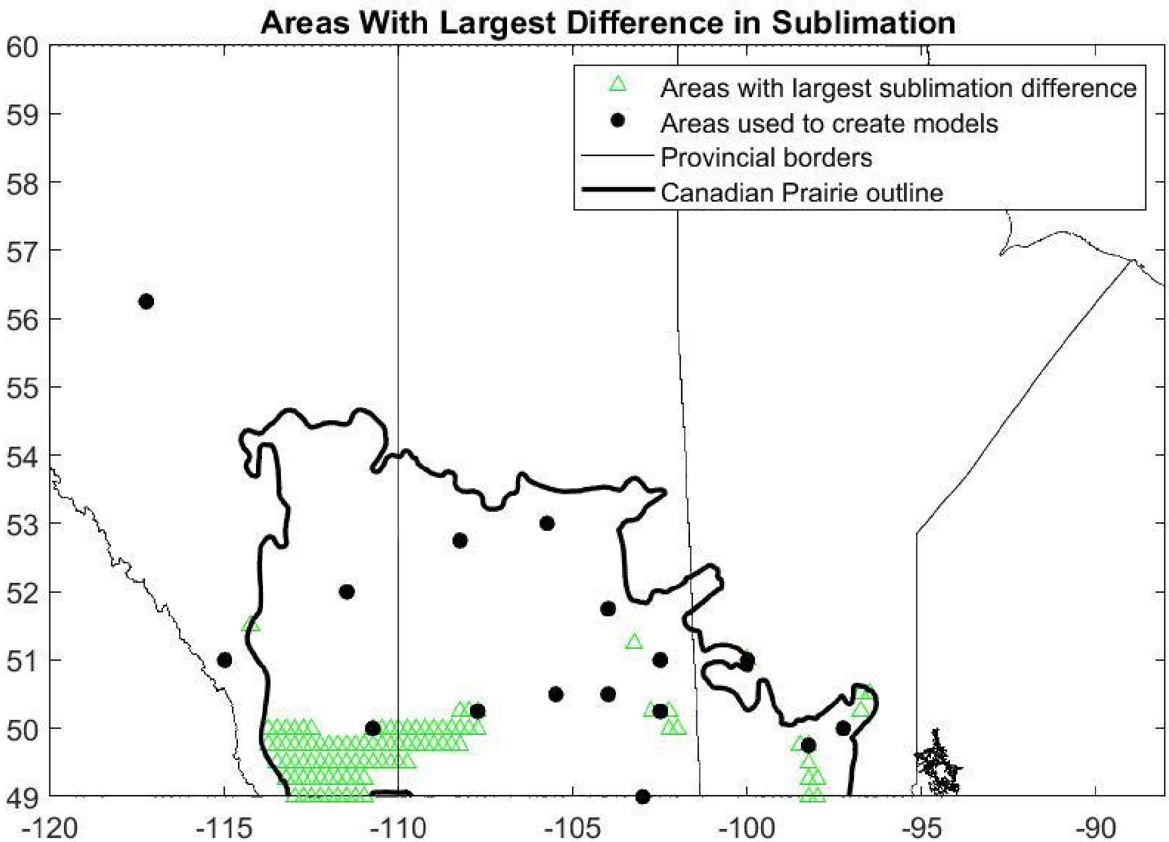

Figure 9) Areas where using stubble conditions is most effective to combat snow loss from sublimation.

<u>3.3 Months WIth Greatest Stubble Impact</u>

November and December were found to have the greatest increase in snow retention in stubble conditions relative to fallow conditions as well as greatest difference in transport and sublimation relative to average season snowfall (Figures 10 - 13). January also had a noticeable area with a large reduction of transport under stubble conditions, but there are also a substantial number of areas where the model is not physically sensible. The change in sublimation loss relative to fallow conditions shows a large decrease in April, although the same trend is not seen with sublimation change relative to season average snowfall.

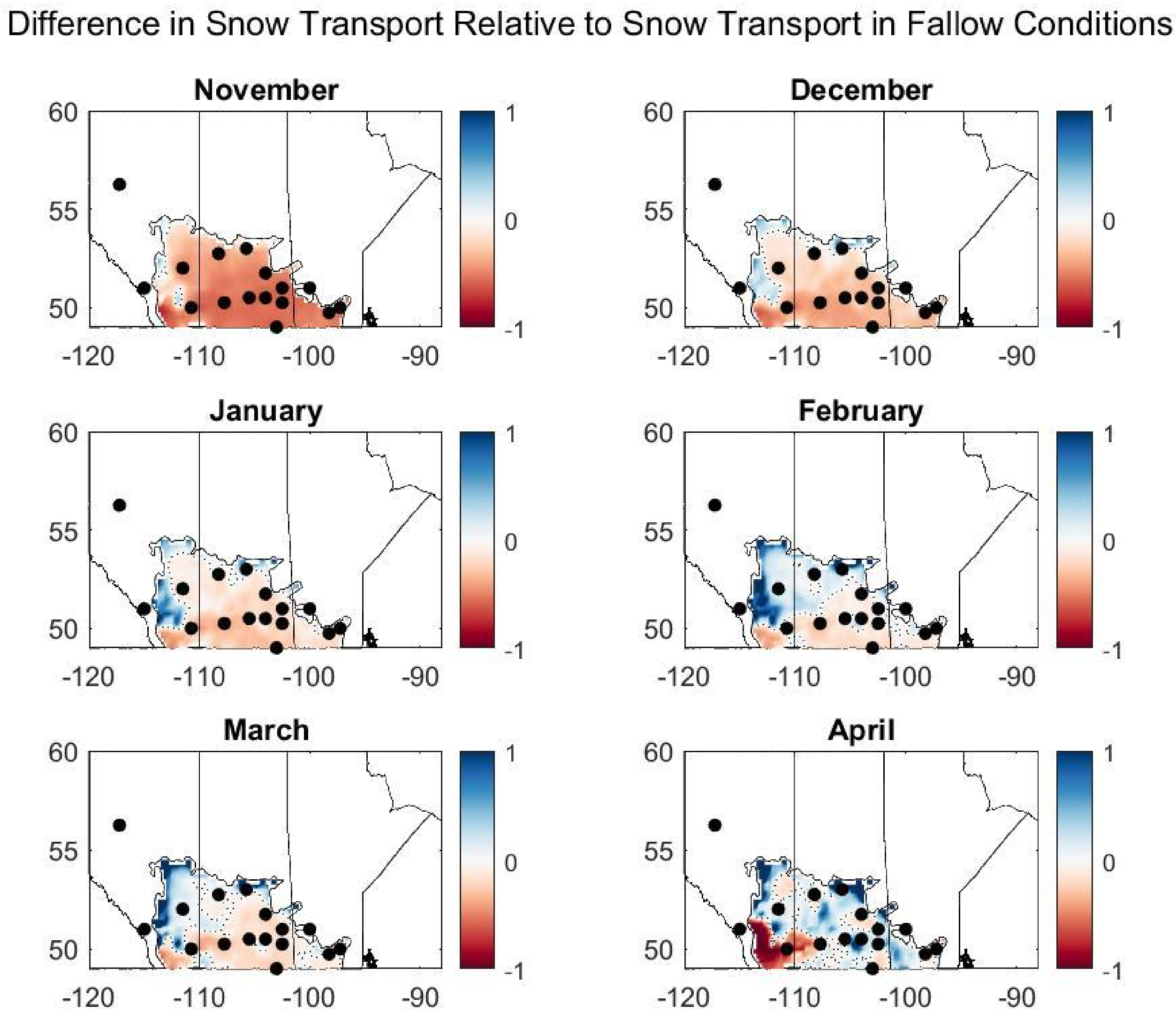

Figure 10) Change in snow retention using stubble conditions relative to fallow conditions through transport. Areas with more negative (darker red) values benefit most from using stubble fields to combat snow loss.

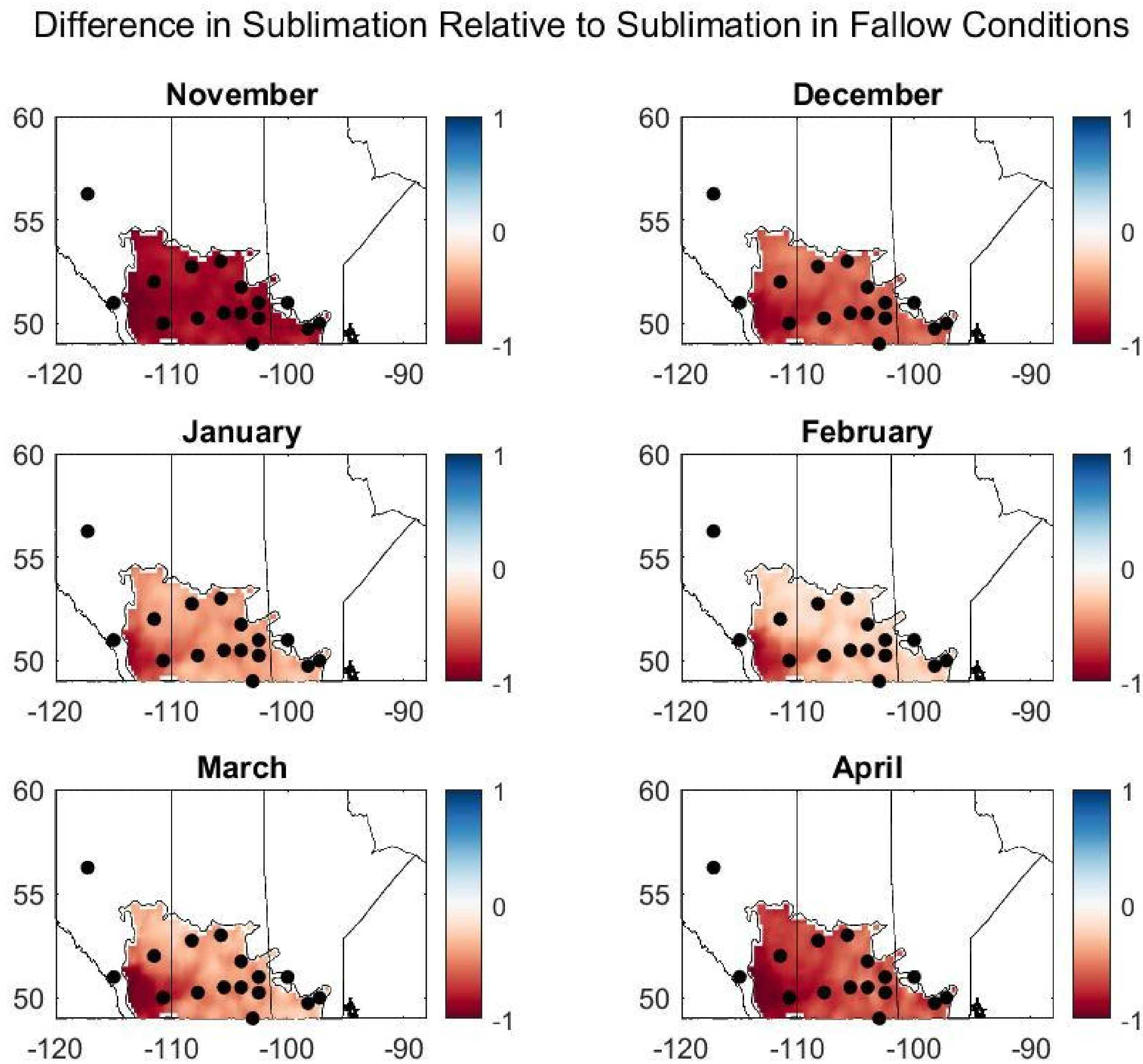

Figure 11) Change in snow retention using stubble conditions relative to fallow conditions through sublimation. Areas with more negative (darker red) values benefit most from using stubble fields to combat snow loss.

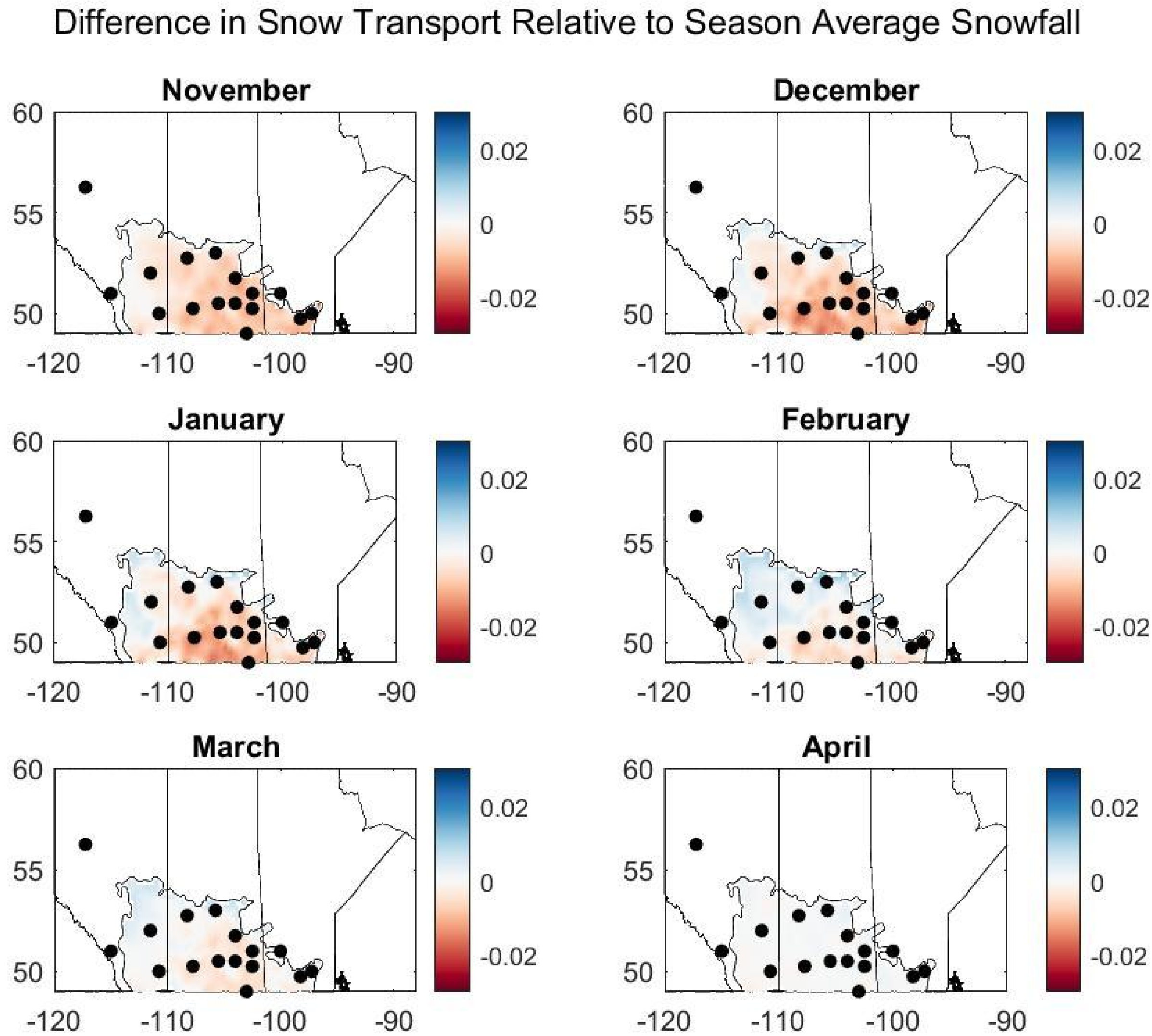

Figure 12) Change in snow retention by transport using stubble conditions relative to season average snowfall.

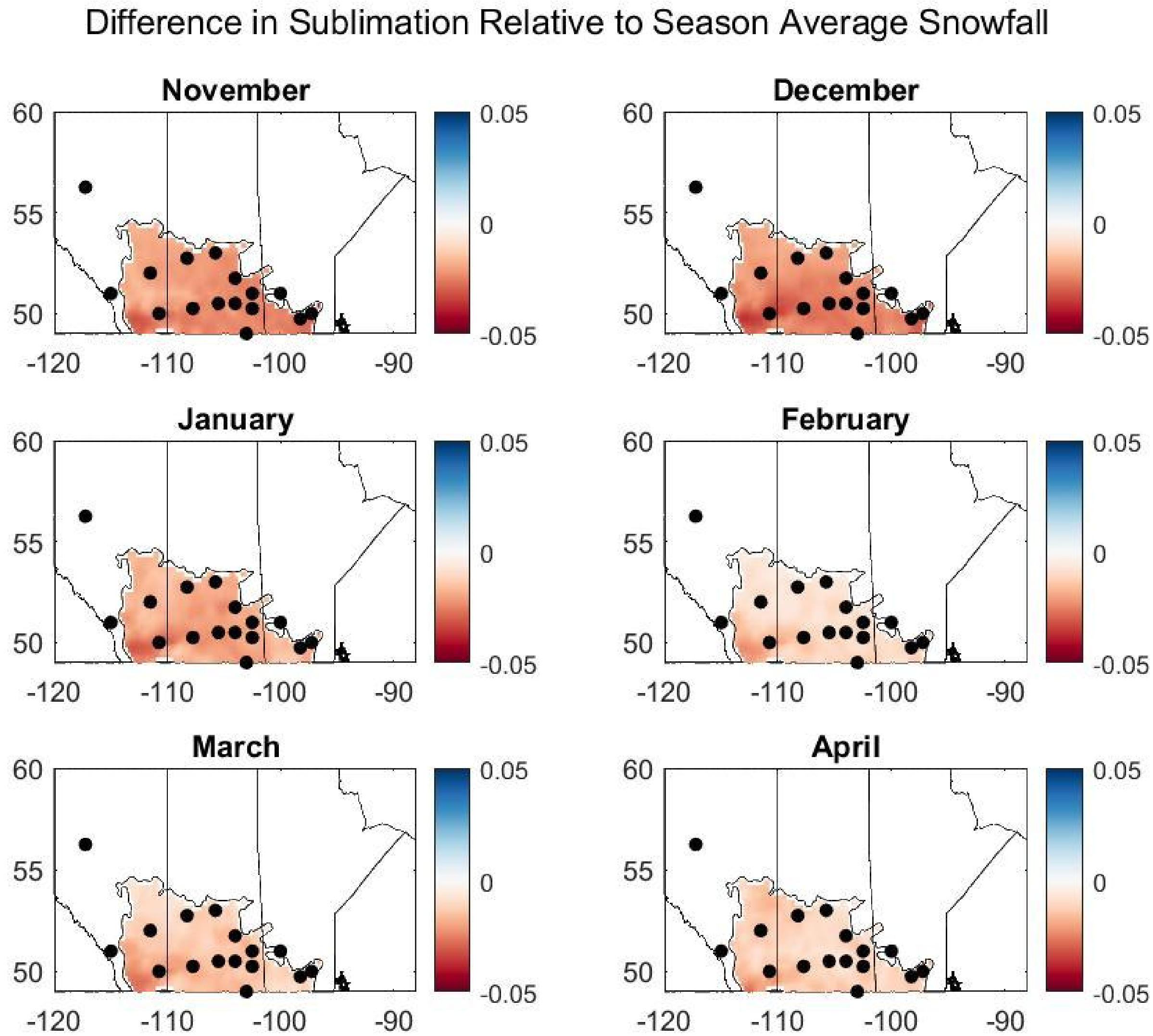

Figure 13) Change in snow retention by transport using stubble conditions relative to season average snowfall.

4. Discussion

The PBSM linear regression model by Pomeroy & Gray (1994) was tested across the Canadian Prairies from 1979 to 2021 to find a) validity of the model, b) areas where field conditions have the greatest impact on snow retention, and c) months where field conditions have the greatest impact on snow retention. From the results regarding validity, it is noticed that the model is the most accurate from November through January in southern Alberta and part of southern Saskatchewan. These are the areas and time periods where the model is best used. This is also the period of time in which stubble conditions have the largest effect on snow retention for transport and stubble, as well as the same spatial area where sublimation difference is greatest. This finding is important because the areas where the model is most physically consistent are also where stubble prevents snow loss by sublimation the most, meaning that in terms of sublimation loss, the model is most trusted where stubble conditions are most useful. The area of greatest change in transport does not correlate as strongly with the validity of the transport model, as stubble decreases transport the most throughout southern Saskatchewan.

The study by Pomeroy & Gray recommends not to use the linear models outside of the Canadian Prairie region due to the area's unique weather patterns. However, this study found that the model is not consistently physically sensible even within the region, and as such, we do not recommend using it throughout the entire Prairie region. The areas that were less physically sensible were consistently colder, more humid, and had greater snow depth. In equations 6 and 7, wind speed has the largest effect on sublimation and transport, but there is not a large variation in wind speed across the prairies, so wind is not a deciding factor on where the model is sensible (Appendix, Figure 9). Out of the variables that most influence validity, snow depth is the most inconsistent over space, with areas of low validity having noticeably greater snow depth. Aside from April, the months of lower validity also have higher snow depth. As seen in Figures 4-6 in the appendix, April has noticeably different values for some inputs compared to the rest of winter, so it is reasonable to see inconsistent and unrealistic results over space.

Southern Alberta is home to the majority of wheat and barley crops in the province (Ramankutty, 2008). Based on the results of this study, we can expect that wheat and barley growth in Alberta would benefit greatly from using stubble fields to combat loss by sublimation. This is important for the country as a whole, as Alberta has historically produced over 40% of the nation's barley and over 25% of the nation's wheat (Ren, 2012). These products are then used within the Canadian food industry as well as exported to the United States and, to a smaller extent, a number of other countries (Government of Alberta, 2021). In a similar case, Saskatchewan produces nearly 90% of the country's lentils (Statistics Canada, 2022). We can expect to see stubble increasing snow retention throughout southern Saskatchewan, which would benefit a large portion of the country's lentil producing farms.

5. Conclusion

This study aimed to find where and when stubble fields have the greatest effect on snow retention in the Canadian Prairies using a set of linear regression models from Pomeroy & Gray (1994). It was found that stubble reduces transport the most in southern Saskatchewan and a small part of southern Alberta, and sublimation the most in southern Alberta plus part of southern Saskatchewan. The months in which stubble fields reduce transport and sublimation by the largest amount are November, December, and January. The models are most physically sensible in southern Alberta, November through January. The areas where stubble fields increase snow retention the most are home to some of Canada's highest wheat, barley, and lentil production.

APPENDIX

$$SWE = 2.39d + 2.05$$

Equation 1) Conversion of snow depth (d, units: cm) to snow water equivalent (SWE, units: mmSWE) in the Canadian Prairies (Pomeroy & Gray, 1995)

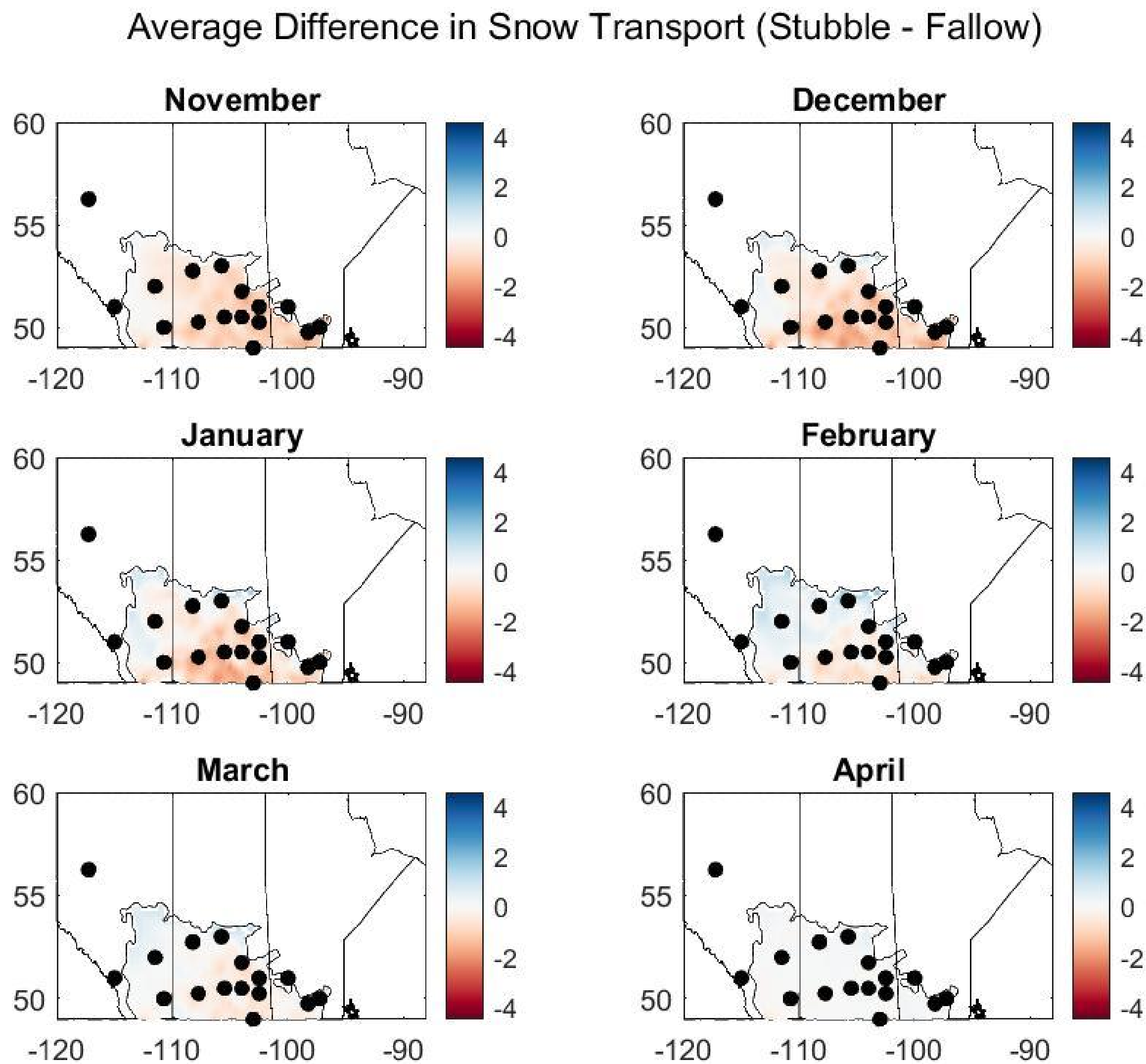

Figure 1) Change in amount of transport out of fields between fallow and stubble conditions (mmSWE). More negative values (darker red) mean larger amounts of snow retained from stubble conditions.

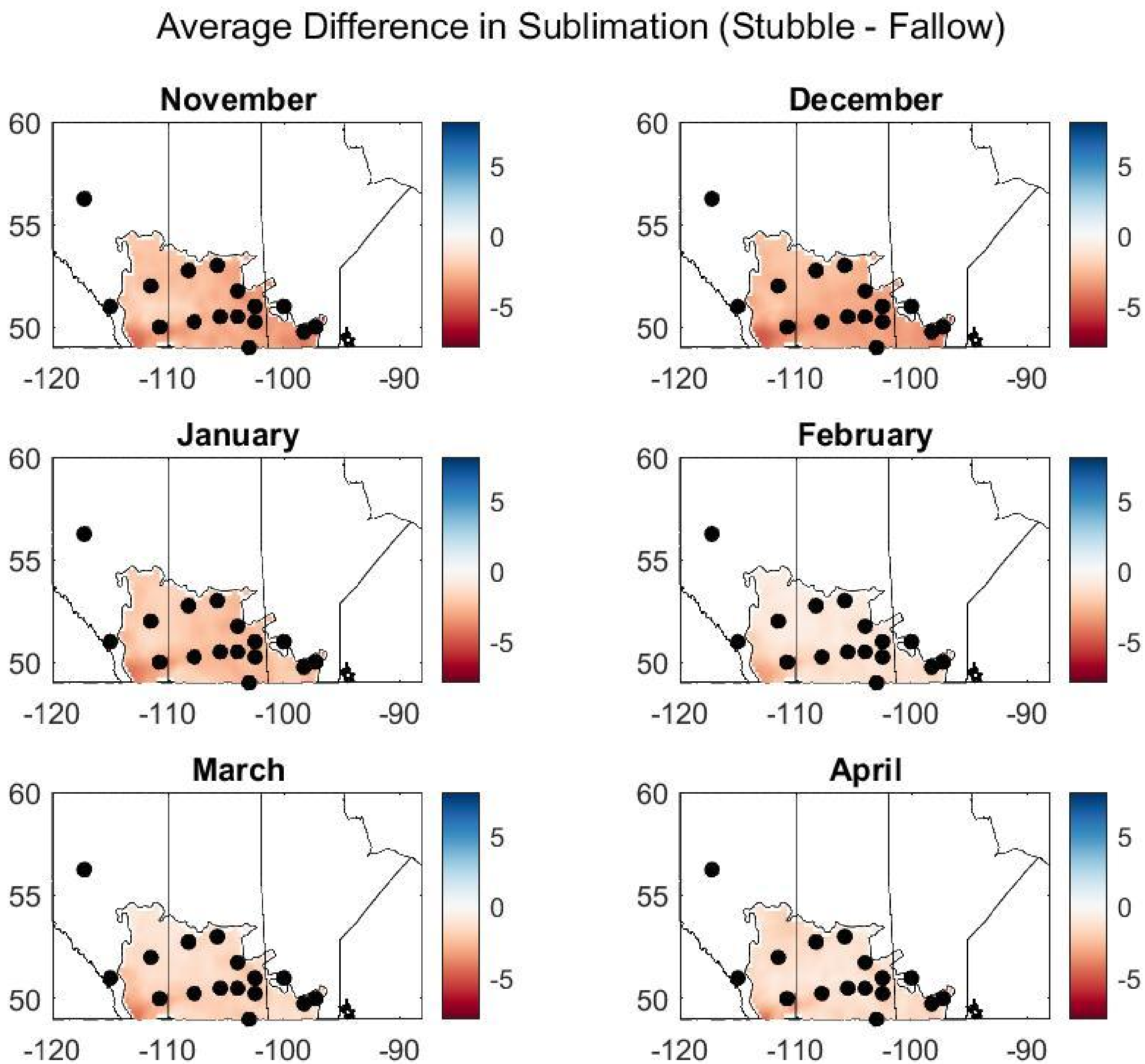

Figure 2) Change in amount of sublimation out of fields between fallow and stubble conditions (mmSWE). More negative values (darker red) mean larger amounts of snow retained from stubble conditions.

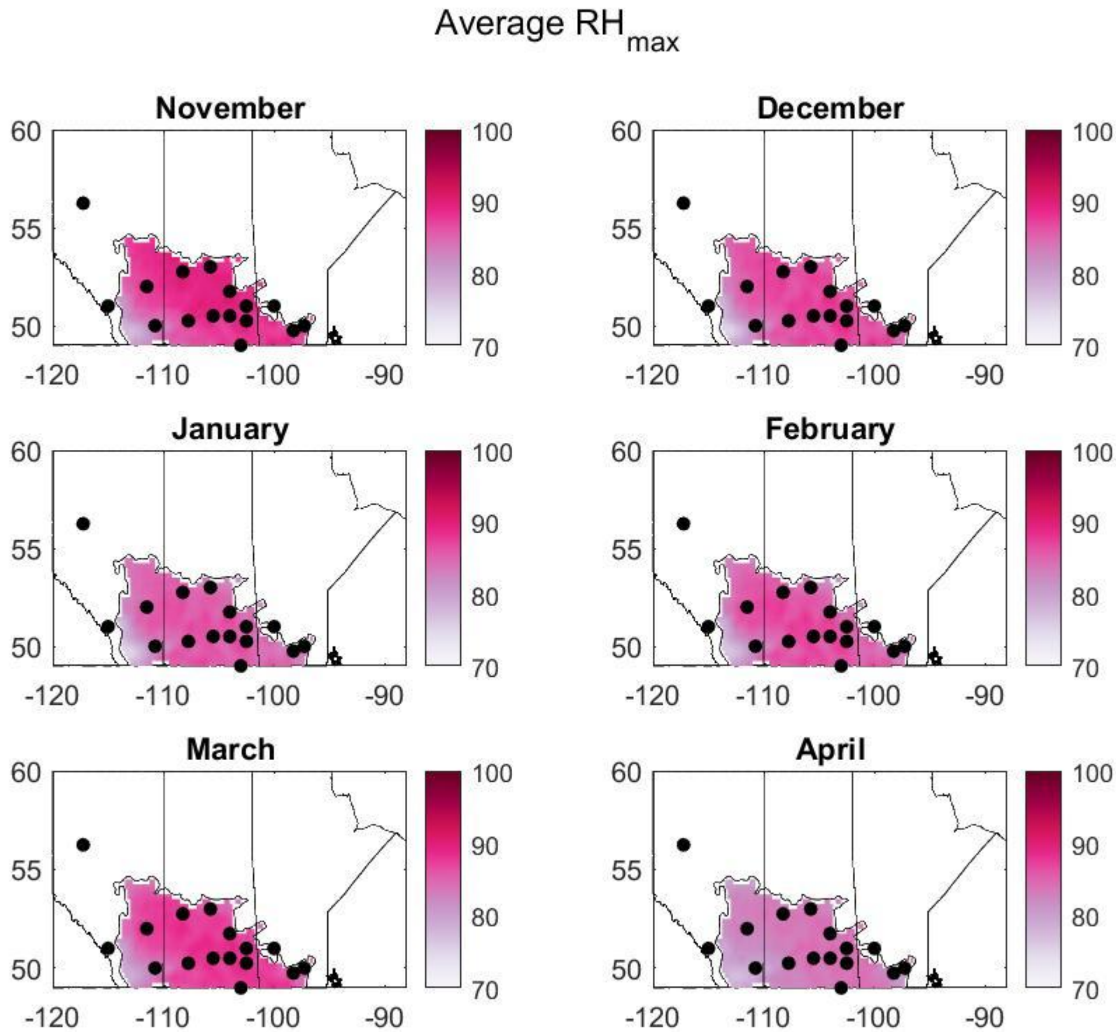

Figure 3) Average maximum relative humidity (%)

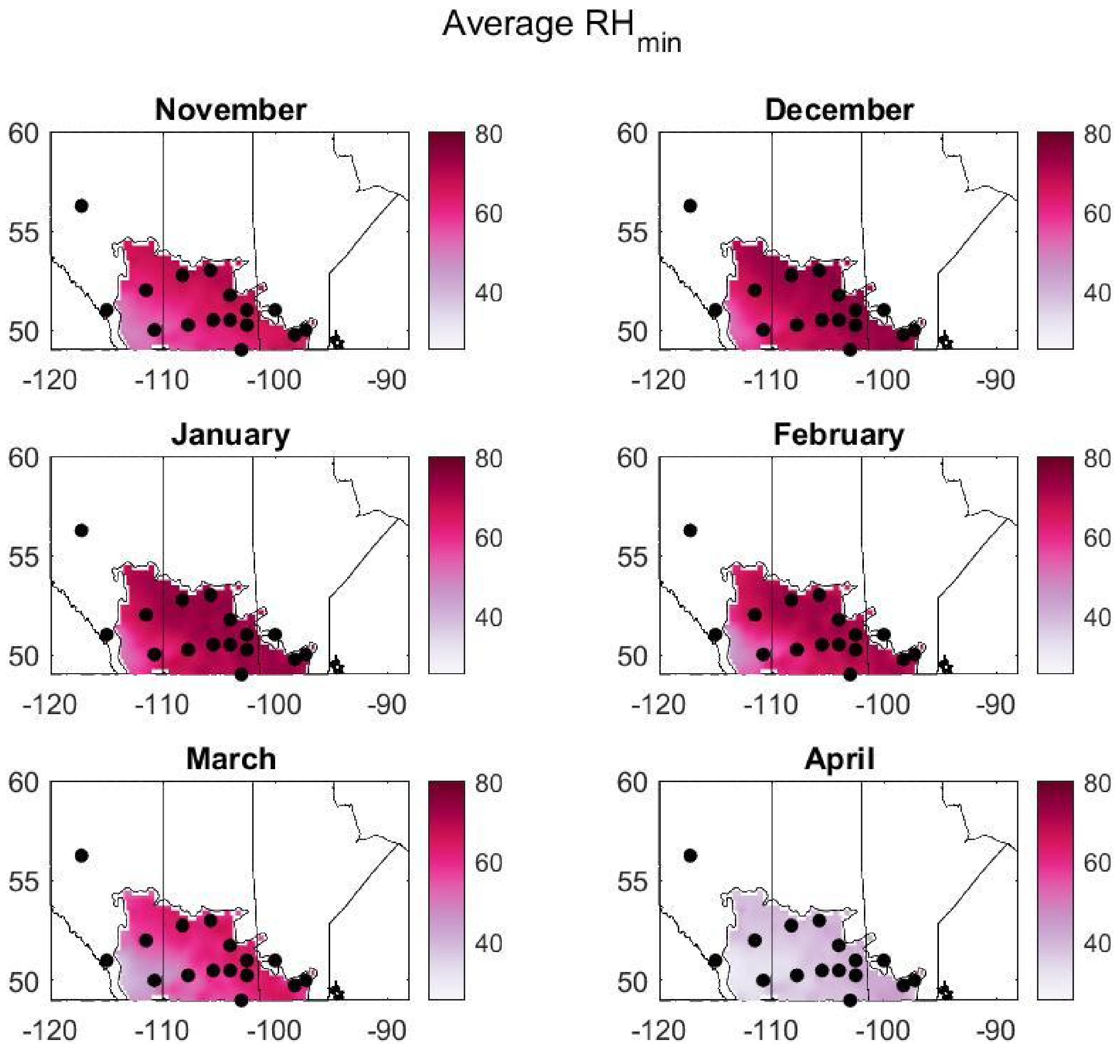

Figure 4) Average minimum relative humidity (%)

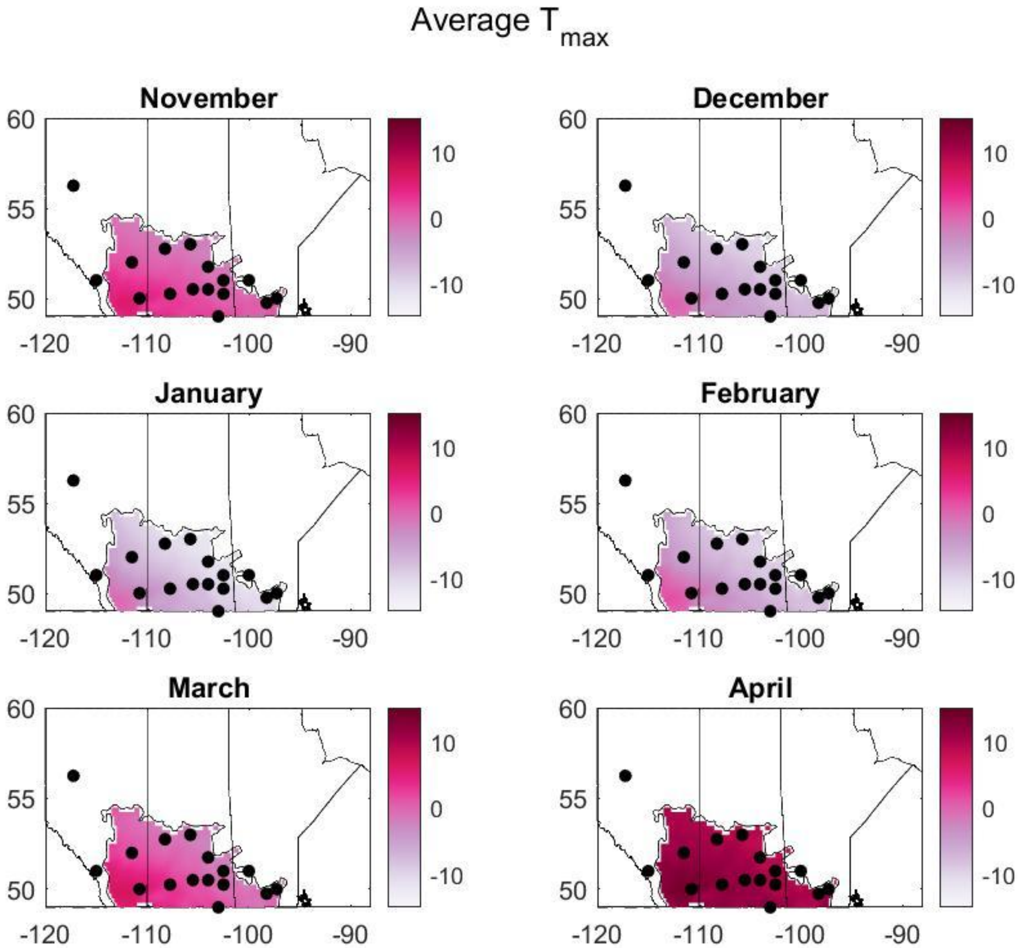

Figure 5) Average maximum temperature (°C)

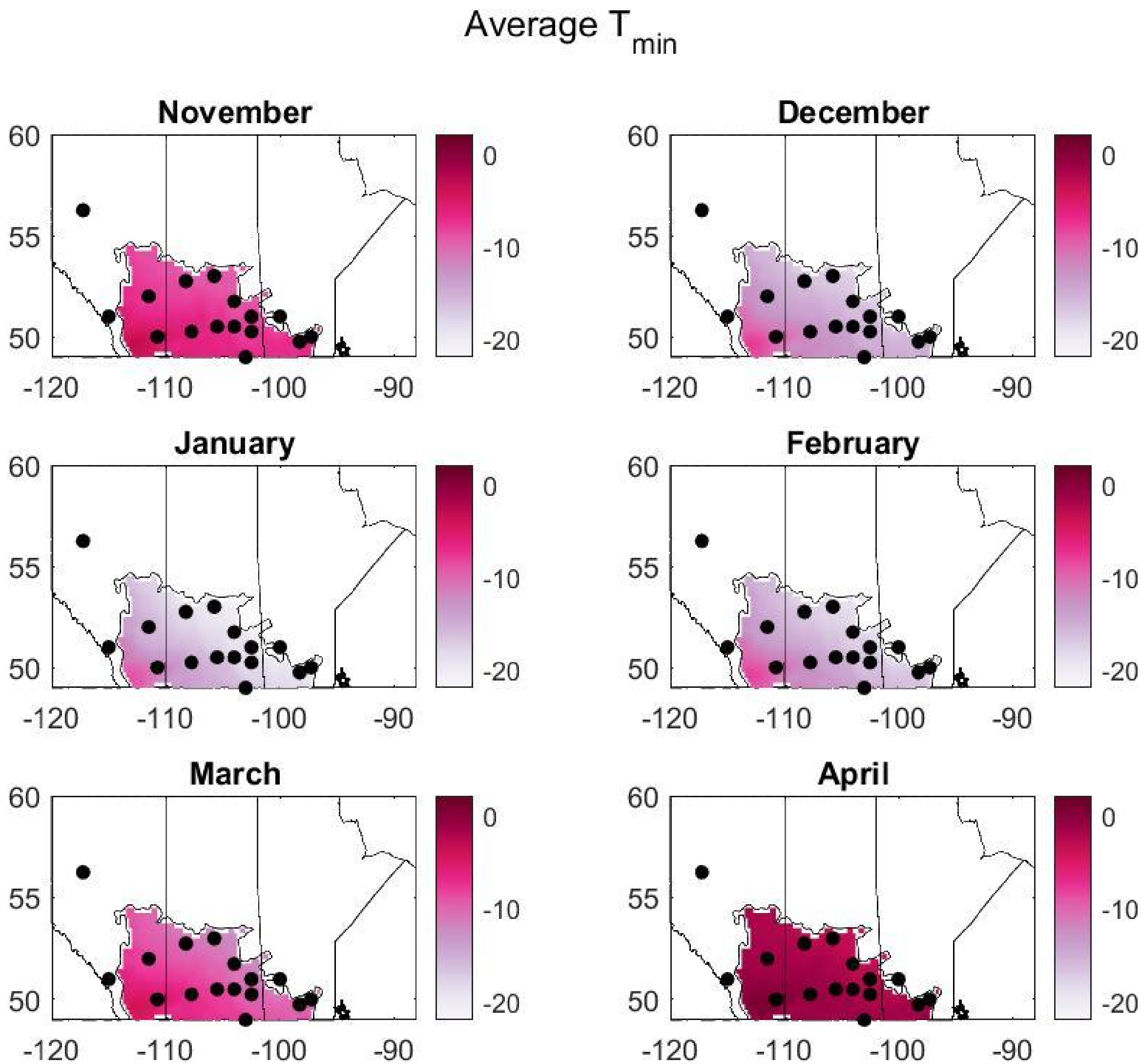

Figure 6) Average minimum temperature (°C)

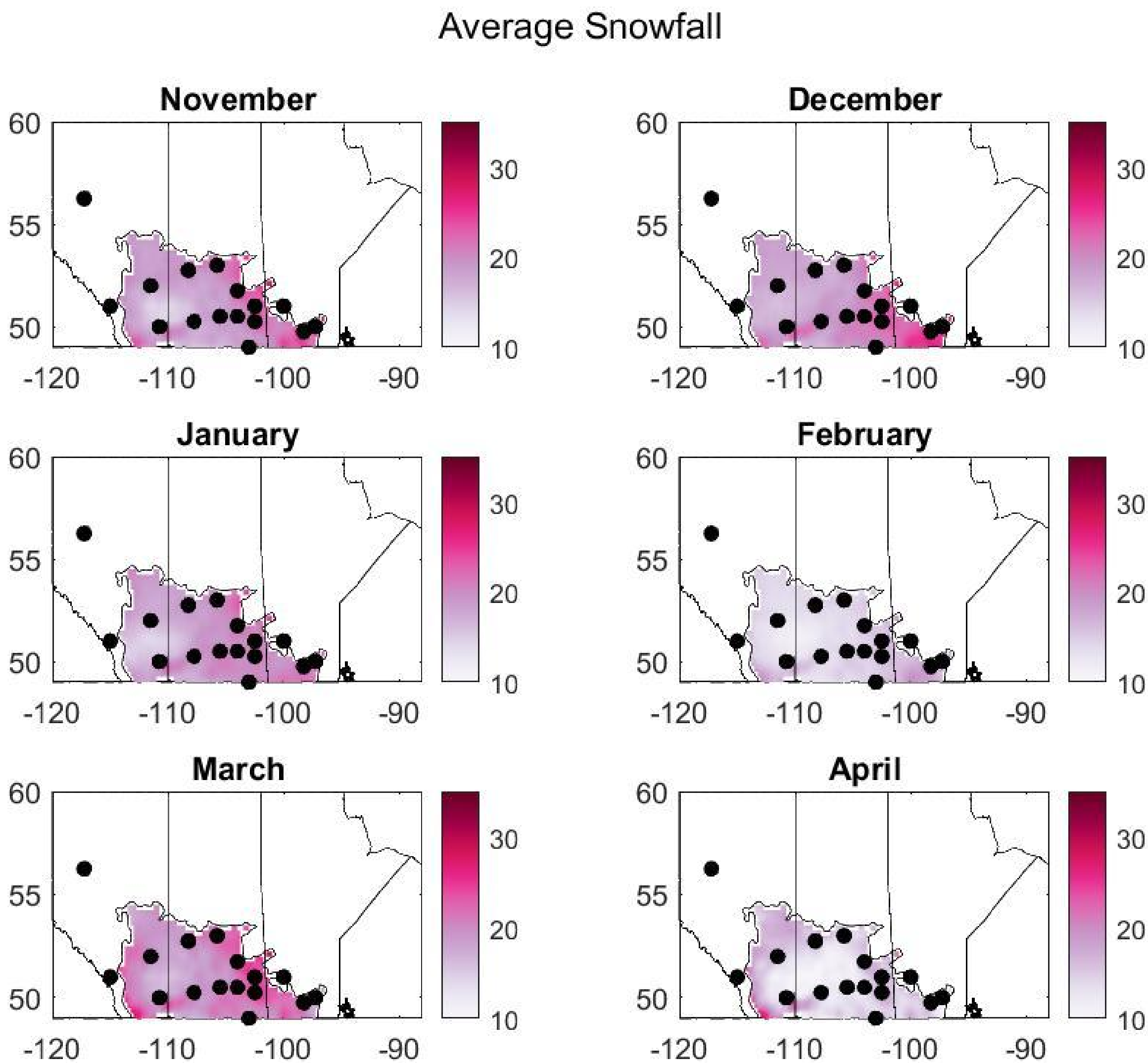

Figure 7) Average snowfall (mmSWE)

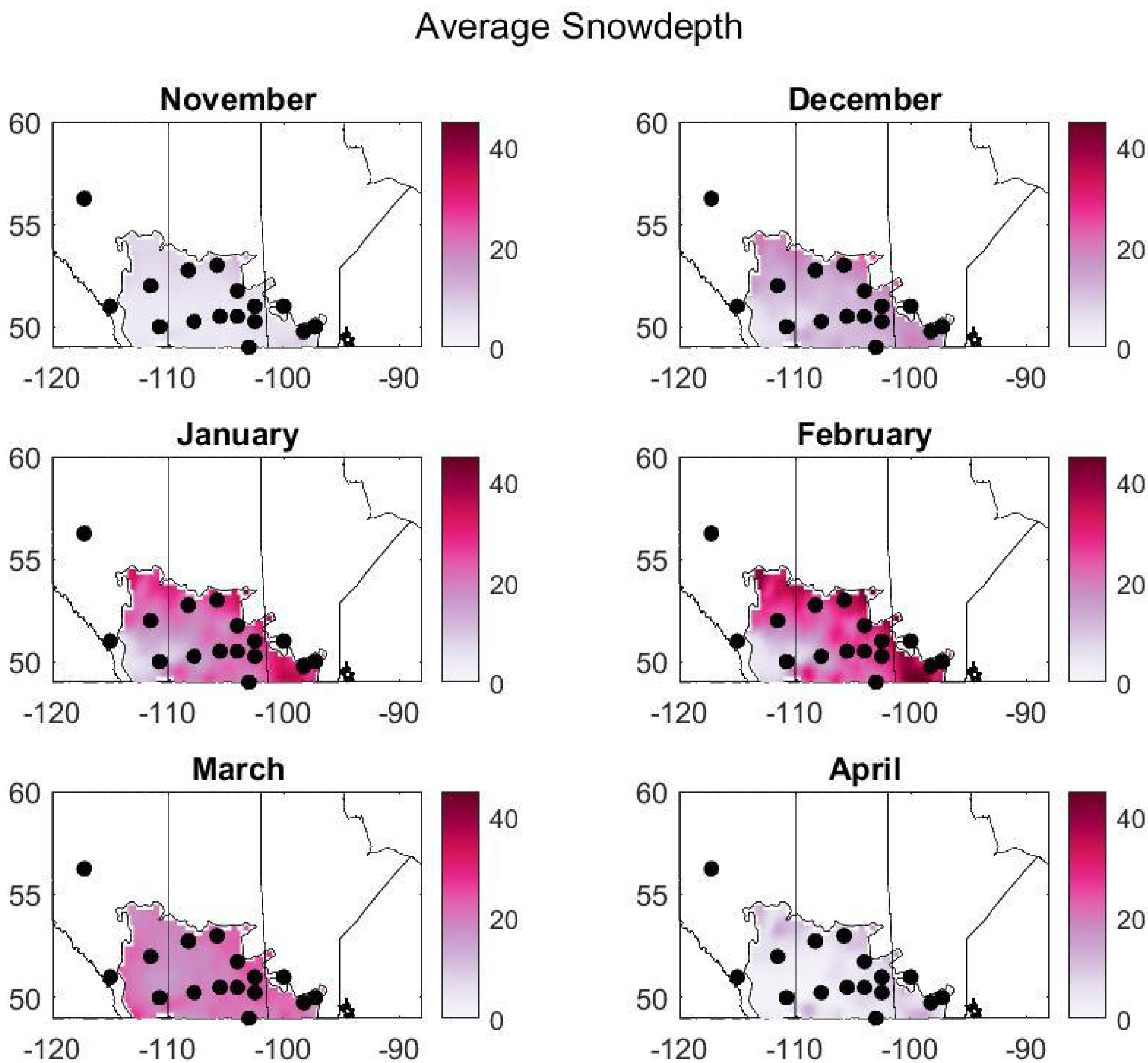

Figure 8) Average snow depth (mmSWE)

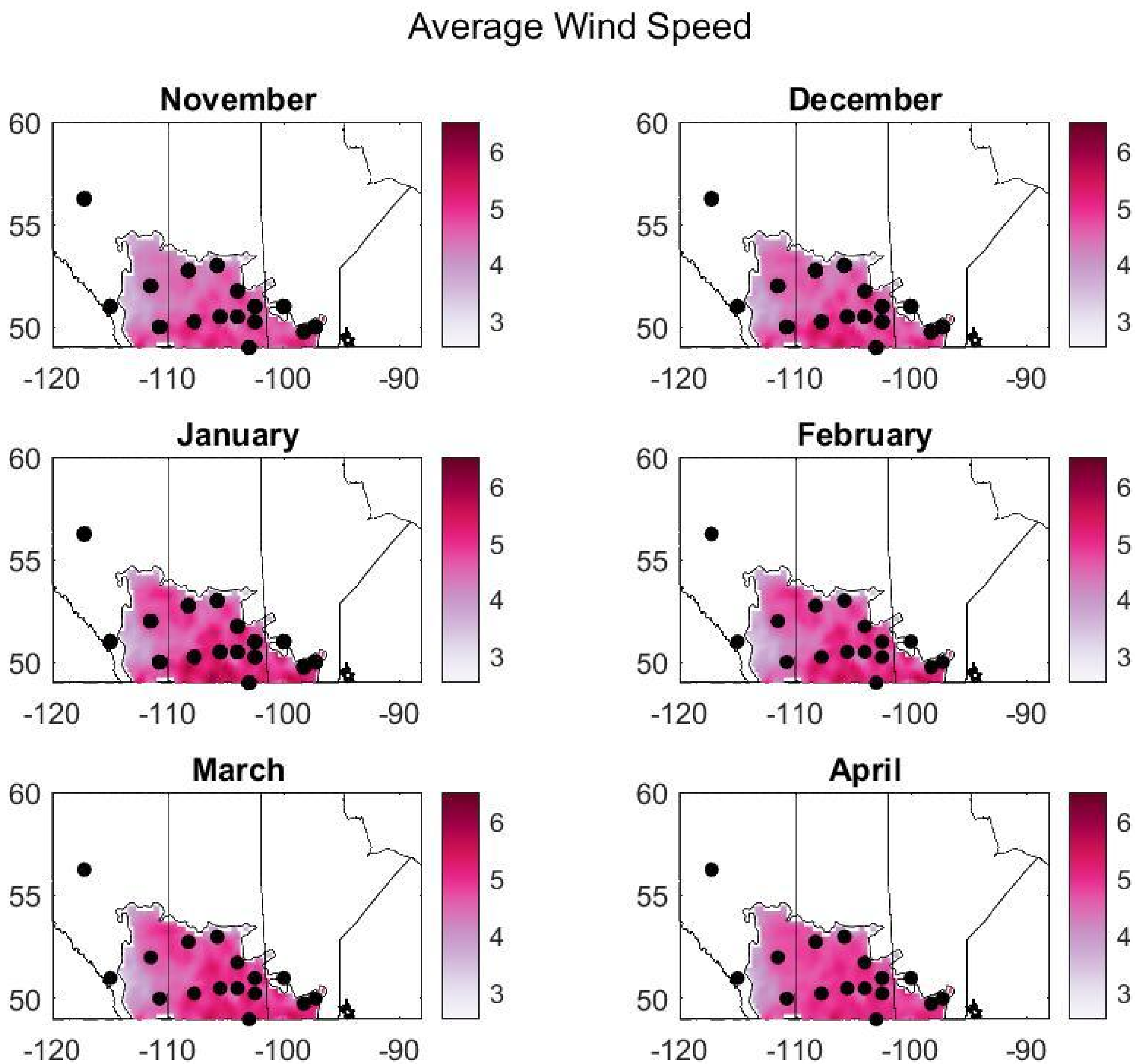

Figure 9) Average wind speed (m/s)

Citations

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