Blowing snow redistribution

Pascal Hagenmuller*

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Abstract

Considering the importance of snow hydrology for water supply in the Canadian Prairies, and the impact of blowing snow processes on the amount of snow available for spring melt, there is a need to develop models of blowing snow transport and sublimation in alpine terrain. A distributed model of blowing snow model (DBSM) was developed by Essery [2] based on MS3DJH/3R terrain wind flow model and the Prairie Blowing Snow Model (PBSM,[9]). This model applied to rolling topography (Trail Valley in the arctic tundra) showed good results. In our study, an attempt was made to run DBSM over steep mountain topography in Marmot Creek Basin, Canadian Rocky Mountains and to assess its performance.

Breaking the assumption of rolling topography, the accuracy of the linear wind flow model is challenged. Using LiDar data for elevation and snow depth and observations from different weather station in the basin, the behaviour of the wind flow model for calculating blowing snow was tested. Although the model must show serious deficiencies in modelling wind on steep slopes, some observed features of redistributed snow covers might be reproduced.

As an alternative, a commercial wind flow model (Windsim) using a 3D Reynolds averaged Navier-Stokes equations and the $k-\epsilon$ turbulence model was coupled to DBSM. This model showed promising results in the complex mountain topography. Nevertheless, the limited number of cells is too coarse to predict complex wind regimes, which are affected by fine scale topographic configurations.

Both model do not reproduce the features of wind blowing over ridges. So, eventually, this particular case of blowing snow process is studied through a two dimensional approach with Ansys CFD program.

Au vu de l’importance de l’hydrologie de la neige pour les ressources en eau des Prairies canadiennes et de l’impact du vent sur la redistribution de ce bien précieux, il existe un besoin fort de développement de modèles des processus éoliens de transport et de sublimation de la neige. Un modèle distribué simulant ce phénomène a été développé par Essery [2]. Ce modèle basé sur le “Prairie

*Département de Mécanique, Ecole Polytechnique, Paris, France
Blowing Snow Model" (PBSM, [9]) et le modèle éolien MS3DJH/3R s’est montré performant dans la relief doux de la Trail Valley (tundra arctique). Dans cette étude, nous tentons d’appliquer ce modèle dans le relief de montagne du bassin de Marmot Creek, Kananaskis. Nous testerons, en particulier, la validité du modèle éolien.

L’hypothèse de relief doux n’étant plus vérifiée, le modèle de vent linéaire et original de DBSM est mis à l’épreuve. Son comportement est testé à l’aide des données expérimentales des différentes stations météo du site et grâce aux données fournies par le système LiDar. Bien qu’il montre de sérieuses insuffisances dans la prédiction dans les fortes pentes, certaines caractéristiques de redistribution de la neige sont reproduites.

Le modèle commercial Windsim qui implémente le modèle de turbulence $k – \varepsilon$ est proposé en alternative. Il montre des résultats prometteurs dans ce type de relief. Néanmoins, la version d’évaluation utilisée limite trop l’échelle spatiale de modélisation, et les effets dus aux configurations du relief plus fines ne sont pas observés.

Enfin, ces deux modèles échouent dans la simple modélisation du vent sur une arête. Il ne reproduisent pas une zone “au vent” et une zone “sous le vent”. Ainsi, une approche en deux dimensions avec le logiciel Ansys est proposée pour simuler les processus éoliens dans cette configuration particulière.
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1 Introduction and objectives

Water supply in Alberta and Saskatchewan have strong economic and social impacts, out of the importance of agricultural, industrial and municipal activities. Because of the geological history of the Canadian Prairies, ground water is not sufficient to all such needs. The major part of the water used in Saskatchewan comes from river flows. The three major tributaries of the South Saskatchewan river have their headwaters in Albertan part of the Canadian Rocky mountains. In summer, the main part of their water flow comes from snow melt. Contrary to a widespread belief, glacier melt waters contribute to less than one percent of the annual flow of the Bow river, the second major tributary of the Saskatchewan river. Consequently, snow hydrology is key for understanding and managing water supply in the Canadian Prairies.

In alpine regions, blowing snow redistribution and sublimation during the winter together with melt are the major processes governing the amount of water available for spring run-off. Pomeroy and Li [10] found that blowing snow processes were responsible for removing 48% to 58% of snow fall in Prairies environments. Because of the high wind speed regimes encountered in some part of alpine watershed, those processes should very likely play a great role in these environments as well.

On contrary to melt which is local, blowing snow processes are spatially distributed. Thus, there is a need to develop spatially distributed model. Essery et al [2] created in 1998 a distributed model of blowing snow transport and sublimation over complex terrain, DBSM. They used a physically-based model of blowing snow (PBSM; [9]; section 2) and the MS3DJH/3R terrain wind flow model. This model was applied to an arctic tundra basin. A reasonable agreement with results from snow surveys was obtained.

The main objective of this project is to apply DBSM in a mountain basin. The wind flow model was developed for rolling topography. Using Mason and Sykes ([7]; section 4) mathematical theory, it has a fundamental assumption of low and continuous slopes. Therefore, applying this model to an alpine area is quite uncertain. The first step of this project is to test DBSM wind flow model in this mountain environment. The Centre for Hydrology has access to several met stations (section 3) providing wind measurements all over the studied basin (Marmot Creek) and a high accurate snow depth map for the whole basin. DBSM behaviour will be tested according to these measurements.

The second objective of the project is to examine an alternative wind flow model (section 5). The chosen model is a simulator for optimizing the energy production from wind turbines, called Windsim. Windsim is based on a 3D Reynolds Averaged Navier Stokes solver. Solving the non-linear transport equations for mass, momentum and energy makes Windsim a suitable tool for simulations in complex terrain. The output of this programme was converted to be compatible with a modified version of DBSM. The results were confronted with measurements to determine if there are any improvements, compared to the original DBSM.

Both model do not give good wind predictions for the “simple” configuration of a alpine ridge. The three stations at Fisera Ridge placed on the upwind side, down
wind side and on top of the ridge are valuable observations to confront the simulations with reality. A simulation (section 6) of this particular site is computed through a two dimensional approach using a Computational Fluid Dynamics program (Ansys FLOTTRAN).

2 The Distributed Blowing Snow Model (DBSM)

DBSM is a distributed model simulating the development of a snowpack over a landscape with varying topography and vegetation cover under the influence of wind transport and sublimation of snow. The model does not take into account melt. The results are therefore only suitable in winter before melt occurs. This three dimensional model requires input files for topography, vegetation heights and a meteorology file at a reference weather station.

The blowing snow process in DBSM is based on the Simplified Blowing Snow Model (SBSM; Essery et al., 1999) who is itself a numerical approximation model of the Prairie Blowing Snow Model (PBSM; [9]). That is not the specificity of DBSM. Other programs as CHRM are implementing PBSM better. What is new in DBSM is the spatial distribution. The transported snow is not just blown away from one cell, it is transported to another. Mass conservation of snow transport is calculated.

2.1 Simplified blowing snow model

2.1.1 Blowing snow transport

![Figure 1: Saltation and suspension transport](image)

Figure 1: Saltation and suspension transport
The rate of mass transport $Q_T$ by blowing snow across a unit width perpendicular to the wind is given by

$$Q_T = Q_{salt} + \int_{h^*}^{z_b} \eta(z) u(z) dz$$

where $Q_{salt}$ is the rate of transport by saltation (Figure 1) in a layer of depth $h^*$, near the surface, $u(z)$ is the wind speed at height $z$ and $\eta(z)$ is the mass concentration of suspended snow who is null over the upper boundary height $z_b$. The Prairie Blowing Snow Model (PBSM) calculates $Q_T$ with this equation. But it can be found that the transport rate depends simply as the fourth power of wind speed with a weak dependence on air temperature. Thus, we have a “model of a model” (SBSM) which simplifies and accelerates the computational calculations. So,

$$Q_T = a(T) u_{10}^4$$

where $u_{10}$ (m/s) is the wind speed at a 10m height, $T$ (°C) is the air temperature, and $a(T)$ the empirical temperature function

$$a(T) = (1710 + 1.36T).10^{-9}$$

The appearance of blowing snow processes depends highly on temperature. For instance, wet snow will not blow away as easily as fresh cold snow. Li and Pomeroy [6] found the following expression for the probability of blowing snow occurrence

$$P(u_{10}) = \frac{1}{\sqrt{2\pi} \delta} \int_{0}^{u_{10}} \exp\left(-\frac{(\bar{u} - u_{10})^2}{2\delta^2}\right) du$$

where the “threshold” wind speed $\bar{u}$ depends on the snow age $A$ (hour)

$$\bar{u} = 11.2 + 0.365T + 0.00706T^2 + 0.9 \ln(A)$$

and

$$\delta = 4.3 + 0.145T + 0.00196T^2$$

For wet or icy snow whatever the temperature is, it is very difficult to initiate transport. So, the parameters for this type of snow are taken to be $\bar{u} = 21$ m/s and $\delta = 7$ m/s. The cumulative normal distribution can also be approximated by

$$P(u_{10}) = (1 + \exp\left(\frac{\sqrt{\pi}(\bar{u} - u_{10})}{\delta}\right))$$

Finally for the time step $dt$ we have a transport of $P(u_{10})a(T)u_{10}^4 dt$ where $u_{10}$ and $T$ are respectively the mean wind velocity and the mean temperature in the time step.
2.1.2 Sublimation rate

In the 1970’s no attention were paid to sublimation losses during transport. But actually more than the third of the snow could sublimate into vapour in some areas. PBSM includes the rate of sublimation over a unit area ground as

\[ Q_s = \int_0^{z_b} \frac{1}{m(z)} \frac{dm}{dt} \eta(z) dz \]

The numerical approximation from SBSM gives an dependence as the fifth power of wind speed.

\[ Q_s = F(T) u_{10}^5 \]

where \( F \) depends only on temperature and takes in account constants as the latent heat of sublimation, diffusivity of water vapour in air, ...

2.1.3 Vegetation influence

When vegetation is higher then the snow depth, the roughness of the ground increases, decreasing the wind erosion effects. From Raupach [11], \( u_{10} \) is replaced in former equations by

\[ u_{veg} = \frac{u_{10}}{\sqrt{1 + 340 z_{veg}}} \]

where

\[ z_{veg} = \frac{N dh}{2} \]

for \( N \) the stalk density, \( d \) stalk diameter and \( h \) the vegetation height above the snow.

2.2 Distribution of the model

![Spatial discretization and distribution](image)

**Figure 2 – Spatial discretization and distribution**
The change in snow mass is given by

\[ \frac{\partial S}{\partial t} = S_f - q_s - \nabla \cdot q_t \]

where \( S_f \) is the snow fall rate, \( q_s \) the sublimation rate and \( q_t \) the transport rate. This distribution is discretized into each cell. Sublimation is calculated at the centre of each box and transport rates across the boundaries of the box are used in a central difference approximation for \( \nabla \cdot q_t \), illustrated in Figure 2. The probability \( P \) of blowing is calculated at the centre of a box and is used to weight the sublimation \( Q_s \) from the box and the transport \( Q_t \) at its outflow boundary. We have so the following local snow fluxes for each box:

\[ S(i, j, t + dt) = S(i, j, t) + dt[S_f - P(i, j)Q_{s,t}(i, j) + n \cdot (T_W - T_E + T_S - T_N)] \]

where \( n \) is a unit vector parallel to the wind. Moreover, we consider periodic boundary conditions for the transport fluxes.

Actually, these transport equations are valid for a minimum fetch (typical length of no configuration changes) of 300 m. PBSM was developed for steady state flow over level terrain! In the mountains the fetch is never this large. A further study should invest this point in details. However, we will still work with these “shaky” equations.

### 2.3 Some details of implementation

DBSM is coded in FORTRAN. It does not need too much computer resources. For example, it takes an hour on my laptop to run DBSM through winter with a 512*512 points space grid and a 30 min time step. The usual spatial grid is around 10 m and the time step about 15-60 min. The programme needs a weather, a topography and a vegetation file in input. The files format is ASCII. The vegetation and elevation files were made by the LiDar system (see Section 3.3). The vegetation height is used to calculate the roughness of the ground. The topography is used to compute the wind map of the studied basin. The wind is discretized into 8 principal directions. The wind values are calculated at 2m height above the ground (numerical factors to fit with \( u_{10} \))

![Discretized wind coming direction](image)

Figure 3: Discretized wind coming direction (N : 0°, NE : 45°, ..., NW : 315°)
The wind map is calculated just at the beginning of the simulation for each direction. The effects of the snow depth on roughness are not taken in account. Actually, DBSM wind model does not care about roughness at all. The model is linear in wind speed. So for each wind speed given by the reference station the program adjusts the wind speed everywhere with just a numerical factor.

The meteorology file contains on each line a time stamp (year and fractional Julian day) and measured air temperature (°C), relative humidity (%), wind speed (\(ms^{-1}\)), wind direction (degrees clockwise from north) and snowfall rate (\(kg.m^{-2}.s^{-1}\)). This values are measured at one of the weather station of the basin (see Section 3). For more accuracy, it is better to take the station that is the nearest to the specified studied area.

2.4 Changes and improvements of DBSM

This study focuses on the wind flow model in DBSM. However, there are only a few wind measurement stations. But through the snow distribution (before melt) given at a high a resolution for the whole basin by the LiDar system, one can come back to a kind of a realistic wind map. I have made some small improvements of DBSM for the mountain environment in order to limit the errors not due to wind flow model. Moreover to test easily different wind flow model in DBSM, I have separated the wind module from the rest of the calculations.

2.4.1 Temperature dependence

The former version of DBSM consider that temperature is everywhere equal to that at a reference station. For low hills, this is sufficient but for high elevation differences, it is not. Actually, temperature plays a great role is blowing snow processes. A FORTRAN subroutine calculates so a new temperature in each grid point. The sun effects are neglected. The simple model used is the following:

\[ T(z) = T(z_{\text{ref}}) + 6.5 \times 10^{-3}(z - z_{\text{ref}}) \]

where \(T_{\text{ref}}\) (°C) is the temperature at the reference elevation \(z_{\text{ref}}\) (m). There is 1500 m elevation difference between the valley bottom (1400 m) and the highest elevation (Mount Allan 2840 m), so we cannot neglect these temperature differences.

Temperature might be not only used to find out the blowing snow wind threshold (see 2.1.1) but also to determine whether it is snowing or raining. DBSM used to consider all precipitation as snow. Of course, this model is supposed to run when there is no melt, so often no rain. But not negligible snow amount can accumulate between rain periods. So, it is important to consider snow/rain events in order to have a precise idea of the snowfall amount. We diagnosed precipitation as rain or snow based on air temperature \(T_a\) using a simple threshold at 0°C. Observations have shown that snow can fall when \(T_a > 0°C\) (Auer; 1974) but for our study, this level of accuracy is sufficient.
2.4.2 Vegetation roughness

In DBSM, the roughness of the ground depends linearly on the height of vegetation above the ground as \( z_0 = 0.2h \). Actually, we can refine that because at each vegetation height corresponds a type of vegetation. Furthermore, with the altitude we can also interpolate to find whether it is alpine or valley typical vegetation. For instance, Figure 4 shows that above a certain altitude there is no vegetation. The tree line follows quite well the 2250m elevation line. Thus, when LiDar gives us a vegetation height above this elevation, we know that this plant is isolated.

I implemented so a more complex calculations of roughness presented in table 1.

![Figure 4: Vegetation and altitude in Marmot Creek (equi-elevation are 50m spaced and start at 1400m)](image)

This values were taken according to my own observations in Marmot Creek and classic readings on the subject [15].

<table>
<thead>
<tr>
<th>Type of vegetation</th>
<th>( N \left( m^{-2}\right) )</th>
<th>d (m)</th>
<th>h (m)</th>
<th>z (m)</th>
<th>Roughness ( z_0 ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Forest</td>
<td>1</td>
<td>1</td>
<td>&gt; 2</td>
<td>&lt; 2250</td>
<td>0.5h</td>
</tr>
<tr>
<td>Sparse Forest</td>
<td>1</td>
<td>0.8</td>
<td>0.4-2</td>
<td>&lt; 2250</td>
<td>0.4h</td>
</tr>
<tr>
<td>Grass</td>
<td>( 10^3 )</td>
<td>( 10^{-3} )</td>
<td>&lt; 0.4</td>
<td>&lt; 2250</td>
<td>0.05h</td>
</tr>
<tr>
<td>Alpine terrain</td>
<td>1</td>
<td>( 10^{-2} )</td>
<td>&lt; 0.4</td>
<td>&gt; 2250</td>
<td>( 5.10^{-3}h )</td>
</tr>
</tbody>
</table>

Table 1: Roughness table (\( N \) the stalk density, \( d \) stalk diameter, \( z \) the elevation and \( h \) the vegetation height above the snow)
3 Wind data collection in the Marmot Creek research basin

3.1 The Marmot Creek Basin

All of the model forcing data used in the project were collected in Marmot Creek, Kananaskis, Alberta, Canada. Located in the eastern ranges of the Canadian Rocky Mountains, the Marmot Creek research basin drains into the Bow river and South-Saskatchewan system. Overall, the basin has an area of 14 $km^2$ which is covered primarily by mountain and sub-alpine forest with alpine tundra-covered ridge tops.

The watershed was first instrumented between 1962 and 1964 for study of sub-alpine spruce-fir forest hydrology by the Canadian Forest Service, in particular the effect of clear cuttings in alpine forests on the water supply. Data logging ceased in 1987 when the Nakiska ski resort was set, but the experimental site has been recently revived within the framework of IP3 (Improved Process and Parametrization for Prediction in Cold Regions). It has now nine permanent meteorological stations at elevations from 1,450 m to 2,500 m (see Figure 5) collecting precipitation, snow depth, soil moisture, soil temperature, short and long wave radiation, air temperature, humidity, wind speed, and turbulent fluxes of heat and water vapour. In addition to the data from the weather station, data from snow surveys are regularly collected by researchers and students (like me) from the University of Saskatchewan. There are accommodations at the Barrier Lake Station, University of Alberta. The site is seven hours drive away from Saskatoon, so it tends to be more and more automatic (data loggers linked to the Internet, see http://128.233.99.232/).

Figure 5: The different met stations in Marmot Creek
3.2 Surveys and instrumentation

3.2.1 Sites used for the study:

I have not used the data from all met stations. I have focused on the stations where the effects of surrounding vegetation on wind might be insignificant. That is to say: stations in large clearings or the alpine zone, or with an high tower. These stations provide wind measurements and also meteorological data.

Figure 6: Fisera Ridge met station in Marmot Creek (April 2009, Pascal Hagenmuller)

Fisera Ridge (2325 m): this meteorological station is located at the top of a ridge, which is the boundary between the forest and stunted alpine vegetation. There is only very small vegetation around the station. Winds are predominately from the north and are moderate enough to maintain a small snow pack during most of the winter months.

Nakiska Ridgetop (2468 m): due to its high elevation and exposure, this site is dominated by strong winds which prevent the persistence of snow cover. This alpine zone has no vegetation.

Hay Meadow (1450 m): meteorological tower located in a very large levelled clearing thus providing a reference for wind direction and speed. This station is of easy access (about 800 m from the road) which allows for frequent checking of the devices. Consequently, the data are almost complete and more reliable than those from other stations.

Vista View (1956 m): situated in a old clear cut. Surrounded by little young trees in a rolling topography region.

Upper Clearing (1845 m): The main station in Marmot Creek. It is situated in the middle of the forest in a little clearing. But the wind can be measured on the top of a 15 m tower.
3.2.2 Snow surveys

There is a high variability in snow depth, even in a 10 m transect. So, just one measure point given by the sensor at the station is not sufficient. We have to complete these data with “manual” snow surveys. It consists to measure the depth and density with a snow tube at about 50 marked points per site. Moreover, in order to have an accurate idea of snow density in the different layers, a pit is dug and density measured with a scale in each layer (Figure 7). I do not really need these data but I have participated to these activities (5 weeks in Kananaskis).

3.2.3 Wind measurements

Most of the sites are equipped with a propeller-type anemometer with fuselage and tail wind vane (RM young 05103) to measure wind speed and wind direction. It is a simple and robust device. Some of the sites have also an ultrasonic sensor (Metone 50.5, see Figure 8). It measures directly the movement of the air mass. They give the wind direction.
Although the met stations are often checked (1 month maximum delay). Sometimes 
the devices develop problems. For winter 2007-2008 about 5% of wind data are wrong 
or missing. Before using this data, you have to carefully get rid of strange values. For 
little gaps, I copied the previous value. For big gaps, I used the mean value.

The direction of the wind is given according to a reference direction (South). In 
Canada, there is a big difference between the geographical north and magnetic north. 
We cannot use a compass. Thus, this reference direction was set in a approximately 
way : with the sun and a watch. I can expect with this method a precision of +/- 
20°. For Fisera Ridge, I pointed the anemometer on Mount Allan (sharp summit) and 
I noted the given direction value. With a map, I found the real angle between the site 
and this mount. Actually, the wind direction is 10° underestimated. For another site, 
Nakiska Ridgetop, I compared the mean directions between January 2008 and January 
2009. There was a 80° gap. Strange ! Is there a different climate ? No, I found 
out that the site was moved in Summer 2008 and must have not correctly been set ! 
According to a station from Environment Canada situated next to ours, our values 
were 80° underestimated. I could not checked the other sites (sensor on high towers) 
but there might be a +/- 20° error.

3.3 LiDar

The Centre for Hydrology has recently used a new way to get high accurate values for 
topography, vegetation and snow depth and on a widespread basin : the LiDar System. 
The principle is simple but the technology beneath it, is advanced. A plane flying on 
the studied basin sends laser pulses to the ground and receives the echos. The plane 
position is known with a cm precision using a GPS system and reference points on the 
ground. For each emitted laser pulse, there is the possibility of up to four measured 
returns (first, intermediate, last and single returns). A single return corresponds to 
bare ground (or snow ground). For several returns, the first one corresponds to the 
top of the vegetation, the intermediate one to middle of vegetation (or snow canopy) 
and the last one to the ground. LiDar returns on a one meter grid, measurements with 
cm precision. Measurements were made in summer 2007 and winter 2008. Subtracting 
the summer ground elevation measurements to the winter ones, we have access to a 
high resolution snow depth map. Nothing, we could have made with our meter stick in 
avaranches paths !!! With these data, we have a kind of high wind map because where 
there is no snow, there must be a lot of wind. However, this system is very expensive 
and so it was just applied once.

3.4 Data format

DBSM as the program Arcview GIS I used to plot my results, needs ASCII format files. 
Of course, most of the other programs outputs were in a another format... lots of fun ! 
For instance to import the wind dates of Windsim, I had to compute an artificial error 
to get results files. Then I had to assembly the position and the wind values who were
in different files. I had to extend to the right grid scale and finally to write an ASCII file. For LiDar files, I had to do quite the same. It was very time expensive (2-3 weeks). In conclusion, you really have to think first what kind of data format you will use and if it is a right choice. Nevertheless, I coded a lot in FORTRAN for this and I now know this computer language well.

3.5 Wind in Marmot Creek

The mean directions of wind are shown in a wind rose (Figure 9). I have taken only the measured directions when the wind is blowing strong enough (5 m/s for Nakiska, 3 m/s for Fisera, 0.8 m/s for Vista, 2 m/s for Meadow and 1 m/s for Upper Clearing). It avoids meaningless values. And after all this study is about wind in blowing snow process who appears with high wind speeds. Pomeroy and Li found a minimum speed threshold of 4 m/s in [5] for the occurrence of this phenomenon.

![Figure 9: Wind rose for the period January-April 2008 (2009 for Fisera Ridge)](image)

For most of the sites, the wind is coming from a clear direction. For Upper Clearing, there seem to be no real dominant wind direction. The mean wind velocity and the most often wind direction at Marmot Creek sites are sum up in the following table.

<table>
<thead>
<tr>
<th>Site</th>
<th>Fisera</th>
<th>Nakiska</th>
<th>Vista</th>
<th>Meadow</th>
<th>Clearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (m/s)</td>
<td>3.1</td>
<td>5.8</td>
<td>1.3</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>Angle (°)</td>
<td>290</td>
<td>240</td>
<td>210</td>
<td>195</td>
<td>140</td>
</tr>
</tbody>
</table>
4 The Mason and Sykes wind flow model

4.1 Theory

There is no need to go into the details of the mathematical theory but it is still very useful to know the great lines of the theory in order to understand what assumptions were made.

DBSM wind flow model is based on two-dimensional theory of Jackson and Hunt [4] for turbulent flow over a shallow ridge. It was extended by Mason and Sykes [7] in 1978 to three dimensional topography.

4.1.1 Assumptions:

We consider a parallel boundary layer flow approaching the hill, i.e. \( u = u_0(z)e_x \). This first naive assumption is quite challenged for Marmot Creek Basin. This chain of mountain is not isolated and actually not the first one in the Rockies (Figure 10) coming from east, from the Prairies. Nevertheless, the Valley between mountains are quite large in the Kananaskis country. Moreover, we can expect that the characteristic size of atmospheric flows is larger then the size of the studied basin. So we could expect “a bit of uniform” far above the mountains.

\[ u(z) = \frac{u_\ast}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad \text{for} \quad z < \delta \]
\[ = \left(\frac{u_\ast}{\kappa}\right) \ln\left(\frac{\delta}{z_0}\right) = u_0 \quad \text{for} \quad z > \delta \]

where \( u_\ast \) is the friction velocity, \( \delta \) the boundary layer thickness, \( z_0 \) the roughness length, and \( \kappa \) the Von Karman’s constant. We will refer later to \( u_0(2m) \) as the reference wind speed. So the wind is supposed to come gently and homogeneously from one direction with a fully logarithmic curve!

Figure 10: The Marmot Creek Basin in the Canadian Rockies (Google Maps)
We do not consider some hill or other. For the mathematical development, the maximum height of the hill, $h$, must be much smaller than the length scale of the hill, $L$. The slope of the hill is assumed to be small and of order $h/L$ everywhere, so that bluffs or cliffs are excluded. These are the most restricting assumptions for our studies. Figure 12 shows that this assumption is not respected at all for Marmot Creek. The local slope is not regular, with sometimes very high value above 1. The mean slope is around 0.2 and the important assumption $h \ll L$ is not really true!

Figure 12: Elevation and slope profile (mean slope 0.20) from Mount Allan to the Valley bottom (West-East transect)
4.1.2 Great lines of theory

The main idea is classic. The derived equations are dimensionless and small terms are neglected. The size of the perturbed velocity is taken according to the “principe de moindre dégènerescence”. The wind flow is divided in two layers who are made fit with a “raccordement asymptotique”. The obtained equations are solved through an asymptotic development and a Fourier Transform.

4.1.3 Results equation

After all we obtain

\[ u(x, y, z) = u_0(z) + \epsilon u_*, U(x, y, z) \]
\[ v(x, y, z) = \epsilon u_* V(x, y, z) \]

where \( z \) is the elevation above the ground and the perturbation size \( \epsilon \) is

\[ \epsilon = \frac{h \ln^2(L/z_0)}{L \kappa \ln(l/z_0)} \]

and

\[ U(x, y, z) = \frac{1}{2\pi} \int_{\mathbb{R}^2} \mathcal{F}\{z_g\} \frac{k^2}{(k^2 + m^2)^{\frac{3}{2}}} \left[ 1 - \frac{K_0(2(i k z)^{\frac{1}{2}})}{K_0(2(i k z_0)^{\frac{1}{2}})} \right] e^{i k x} dk dm \]
\[ V(x, y, z) = \frac{1}{2\pi} \int_{\mathbb{R}^2} \mathcal{F}\{z_g\} \frac{km}{(k^2 + m^2)^{\frac{3}{2}}} \left[ 1 - \frac{K_0(2(i k z)^{\frac{1}{2}})}{K_0(2(i k z_0)^{\frac{1}{2}})} \right] e^{i k x} dk dm \]

where \( K_0 \) is the modified Bessel function and \( \mathcal{F} \) denotes the Fourier transform. It is a bit hard to imagine wind speed through these equations but we can remember:

- that the perturbation is linear in the upstream wind speed \( u_0 \) (called later reference wind speed). That is to say that a north or south wind gives the same wind speed results in just an opposite direction.
- hopefully the wind speed depends on the whole basin topography through the integral and the Fourier transform.
- the size of the perturbation \( \epsilon \) depends on physical parameters

4.2 Implementation

To calculate the wind map for each discretized wind direction, we rotate the topography in order to have always wind coming from \( x \) direction and so we can directly apply the Mason and Sykes theory. After calculation, we rotate the wind map back to its original direction.
The discrete Fourier transform is computed through a fast Fourier transform algorithm. The gain in computing speed is high. However, there are some added constraints to use this algorithm. The grid has to have $2^b \times 2^b$ points and be square. We have to blend topography into a flat plane, to have periodic boundary conditions. Thus, the results are only realistic within an area who is not affected by this blending. The blending is quite smooth and can be parametrized as following:

$$z_{\text{blend}}(i, j) = c(r) \cdot z(i, j) + (1 - c(r)) z_m$$

with $z_m$ the mean elevation, $r$ the distance to the centre of the grid and

$$c(r) = \begin{cases} 1 & \text{when } r < r_0 \\ \exp\left[\left(\frac{r-r_0}{w}\right)^2\right] & \text{in other cases} \end{cases}$$

where $r_0$ is the radius of the non affected topography and $w$ the typical length of the transition to flat plane. In my simulations, I took care that the blending does not affect the wind calculations at the different Marmot creek stations (see Figure 13).

![Figure 13: Blended topography (right) from the original one (left)](image)

The calculation of the wind map is quite fast. It takes about 5 min to compute the wind map for $1024 \times 1024$ points in 8 directions. Contrary to other wind models, it is not real three dimensional. The grid for calculation is 2D, there is no need to compute wind in upper layers. Furthermore, the model does not care about roughness, so the diminution of vegetation height because of the snow does not affect the wind results. The wind map is computed once for the whole winter. The main advantage of this model is its speed. But are the results good?
4.3 Results

I have run the Mason and Sykes model with a 8 m space grid (1024*1024 points) with the Marmot creek topography given by the LiDar system. The values are taken for a reference top boundary wind speed equals to 1 m/s. First, the global wind map is analyzed to see whether features of wind are respected. Then, I compare the computed wind speed with wind speed given at met stations. Finally the effects on blowing snow processes are analyzed.

4.3.1 Global analysis

Figure 14: Wind map for a SW wind and a 1 m/s reference wind speed. The topography is represented by 50 m equi-elevation lines.

Figure 14 shows the wind speed for the blended topography of Marmot creek. The wind speed is deeply perturbed by high elevation mountains. The highest values (∼4 m/s) appear around ridge tops. On smooth continue slopes (middle of the figure) the perturbation is small (+/- 0.3 m/s).
Figure 15 shows the same wind map zoomed on a ridge perpendicular to the wind. The results are symmetric along the ridge. Actually, that is not true at all. The side of the ridge who gets the wind first should be more windy than the other side. The linearity in wind speed gives the same result for $u_\ast \rightarrow -u_\ast$ i.e. for an opposite wind direction, thus there is a symmetry. That might be true for smooth and small slopes where the wind is “following” the topography but that cannot be applied for sharp ridges where there is a kind of aerodynamic stalling. Nevertheless, the model might predict snow accumulation on the right side: the snow on ridge is blown away to a place where the wind decreases... the down wind side. The amount of snow may however be underestimated.
4.3.2 Comparison with met wind speed

Figure 16 shows the predicted wind speed for five different met stations (Fisera ridge, Hay Meadow, Nakiska Ridgetop, Vista View and Upper Clearing) and for usual wind directions. The wind speed was computed with a 10° scale for the reference wind direction and 1 m/s reference wind speed. Since the model is linear, it is not necessary to compute wind speed for 180°-360° directions. The original wind model in DBSM uses a 45° scale. Indeed if this model is accurate, the scale in wind direction should be smaller (around 10°) to take in account the large variability in wind speed with wind direction. For the non alpine sites (Hay Meadow, Vista View and Upper Clearing) the perturbation is small. On contrary for the alpine sites (Fisera ridge and Nakiska Ridgetop), there is a high variability.
The wind deviation is not well predicted. In comparison with the wind rose (Figure 9), the deviation at Fisera should be about 100° and it is about 20° for the wind flow model. Fisera has a special wind regime (NW) very distinct from the other stations (~SW) and the model is not able to predict it. The scale of deviations for the other stations is acceptable. Local wind deviations may be reproduced but for large scale prediction the model fails totally.

According to Figure 16 and Figure 17, the wind at Hay Meadow should be not influenced by the topography. The deviation is null and the wind speed is always equal to one. So, this site seems to describe quite well the reference wind speed and direction. Thus, to compare the computed wind to the real wind, I have made a linear regression in respect to Hay Meadow wind speed and for each wind direction (10° interval) at this site. Moreover to take in account “real weather” wind and not thermal wind perturbation (“brise thermique”), only the wind above 3 m/s is taken in account. Figure 18 shows the values for usual wind direction at Hay Meadow i.e. where there is more then 50 data points.

Figure 17: Wind deviation of Mason and Sykes model at met stations
The linear regressions for the two Alpine sites (Fisera, Nakiska) fit astonishingly well with the model. The mean wind at Nakiska (resp. Fisera) is 2.5 times (resp. 1.5 times) the wind at Hay Meadow and the predicted linear regression is 2.6 times (resp. 1.3 times). For the other sites, the wind is over predicted. There could be two reasons for that. First, these sites are surrounded by forest. Since the wind flow model does not care about roughness of the ground, wind speed might be over evaluate even if the vegetation is not directly close to the wind instrument. Second, the model is working with a blended topography (see section 4.2). Thus, the Marmot Creek basin is seen as an isolated mountain whose effects on the wind in the surrounding plane are negligible.

Also, the model predicts high variability with the reference wind direction. Actually the wind dates do not illustrate this point. In figure 18, the coefficient of the linear regression is quite constant. More over, there is no significant gain in correlation $R^2$ when making linear regressions with all wind directions together or with $10^\circ$ intervals.

4.3.3 DBSM predicted snow amount

The comparison with met stations data showed that the model was mostly wrong. Actually, we want especially to see if the blowing snow processes themselves are well predicted.

Figure 19 shows the snow depth measure by LiDar on March 27 2008. The dark paths are due to Nakiska ski resort artificial snow. We should keep in mind that at this date melt could have already occurred and that the vegetation effects are not reduced to avoid blowing snow events but might affect in different ways the snow amount. Thus, the most pertinent area for comparison of snow depth between DBSM and LiDar measures is the alpine zone.
Figure 19 shows the predicted snow amount on March 27 2008. The simulation starts on November 1 2007 and uses Hay Meadow met file. The model predicts bare ground zones on top of ridges. Actually, LiDar measures reproduce also this feature but it is not so pronounced. Furthermore the snow accumulation zones do not fit. They are often predicted on to high elevation zones. The predicted strong wind might be too concentrated on ridge top. At Fisera Ridge station, the predicted snow accumulation using the met files from Hay Meadow is on the wrong side of the ridge (see Figure 20 middle). That is due to the fact that Mason and Sykes model is not able to reproduce the particular NW wind regime in this zone. Using the met files of Fisera Ridge station (missing snowfall data interpolated with Hay Meadow ones), the results are suitable (Figure 20 right). DBSM local predictions around a site are good enough but its wind model fails for larger scales.

Figure 20: DBSM predicted snow depth for Fisera Ridge (on March 27 2008). The flag represents the position of the station.
5 A more complex wind flow model: Windsim

Windsim is a simulator for optimizing the energy production from wind turbines. It predicts local wind fields. It is a commercial product. I used the evaluation version which is limited in the grid size. Windsim is based on a 3D Reynolds Averaged Navier Stokes solver. Solving the non-linear transport equations for mass, momentum and energy makes Windsim a suitable tool for simulations in complex terrain, and in situations with complex local climatology.

5.1 Reynolds-averaged Navier–Stokes (RANS) equations

The Reynolds-averaged Navier–Stokes (RANS) equations are time-averaged equations of motion for fluid flow. They are primarily used while dealing with turbulent flows. These equations can be used with approximations based on knowledge of the properties of flow turbulence to give approximate averaged solutions to the Navier–Stokes equations.

5.1.1 RANS equations

We suppose that our fluid is incompressible. Actually the Mach number is here about $M \approx 15/340 \approx 5.10^{-2} \ll 1$. So this assumption is suitable. We also suppose that air is a Newtonian fluid, classic assumption and we neglect gravity. The Navier-Stokes equation are so:

$$\begin{cases}
\partial_t U_i = 0 \\
\partial_t U_i + U_j \partial_j U_i = -\frac{1}{\rho} \partial_i p + \nu \partial^2_j U_i
\end{cases}$$

where $U$ is the air velocity, $\rho$ its density and $\nu$ its viscosity. The idea is then to average in time this equation writing $U_i = \bar{U}_i(x, y, z) + u'_i(x, y, z, t)$. We get

$$\begin{cases}
\partial_t \bar{U}_i = 0 \\
\bar{U}_j \partial_j \bar{U}_i = -\frac{1}{\rho} \partial_i \bar{p} + \nu \partial_j (\partial_j U_i - \bar{u}'_i \bar{u}'_j)
\end{cases}$$

We use the closing Boussinesq relation for Reynolds tensor i.e. we suppose that the unstationary turbulence is proportional to the gradient of velocity. It is easy to understand that where there is a big shear, there might be a lot of turbulence.

$$\bar{u}'_i \bar{u}'_j = -\nu_t (\partial_i \bar{U}_j + \partial_j \bar{U}_i) + \frac{2}{3} k \delta_{ij}$$

where $\nu_t$ is the turbulent viscosity and $k$ is the turbulent kinetic energy.

5.1.2 The $k-\epsilon$ model

The choice of $\nu_t$ is the specificity of the $k-\epsilon$ model developed by Hanjalic and Launder (1972). $k$ designs the turbulent kinetic energy and $\epsilon$ it dissipation rate. We are not
taken an algebraic model with a classic mixing length but we try to relate $\nu_t$ to $k$ and $\epsilon$. For dimensional reasons, we have $\nu_t = C_{\mu}k^2/\epsilon$. Adding these two variables, we need two more equations. Using the general Navier-Stokes equation and the RANS equations, making some manipulations, we have a transport equation for $k$:

$$\partial_t(U_i k) = \partial_i \left( \frac{\nu_t}{\sigma_k} \partial_j k \right) + P_k - \epsilon$$

The same for $\epsilon$:

$$\partial_t(U_i \epsilon) = \partial_i \left( \frac{\nu_t}{\sigma_s} \partial_j \epsilon \right) + C_s1 \frac{\epsilon}{k} P_k - C_s2 \frac{\epsilon^2}{k}$$

where the turbulent production term $P_k$ is:

$$P_k = \nu_t \left( \partial_i U_j + \partial_j U_i \right) \partial_j U_i$$

Few constants appear. There are due to closure relations like the Boussinesq one between a flux and a gradient. These constants are usually tuned to fit basic flow problems where the logarithmic velocity profile prevails. But for Windsim, they were modified to fit with our wind problems.

### 5.1.3 Boundary conditions

Actually, most of the assumptions made for the $k-\epsilon$ model are false next to the ground (or wall). Whatever the velocity is above the ground, we should find a logarithmic profile next to the boundary. So, Windsim (see [3]) makes an artificial layer where the velocity follows a log profile and thus we have a boundary condition a bit above the ground. At the distance $d$ above the ground:

$$k = \frac{U_*}{\sqrt{C_{\mu}}} \text{ et } \epsilon = \frac{U_*^3}{\kappa d}$$

where $d$ is the size of this artificial layer and $U_*$ the friction velocity. In the layer, $k$ and $\epsilon$ are taken from analytical profiles.
5.2 Program inputs

The evaluation version of Windsim has a limited number of cells (5000). The space above the ground is meshed into small boxes. I used 230 m space grid to fit the limited cell number. The imported 8 m topography and roughness from LiDar are automatically averaged into Windsim cells (Figure 21). Lots of details of the topography disappear at this scale; for instance, Fisera Ridge. There is no blending as in DBSM original wind flow model. The boundary conditions are set with a specific wind speed on an upper layer far above the topography (500 m above the highest point in my simulations). I set the number of iterations for the calculation to 100 but the convergence was actually mostly finished around 60 iterations.

Since the wind calculation are not “mathematical preprocessed” like Mason and Sykes model, it takes about one hour to have a wind map for one reference wind speed and eight directions.
5.3 Results

5.3.1 Global analysis

Windsim has a coloured user-friendly interface to plot results (Figure 22). It seems very smooth and has nice precise contours. This smoothing can be somewhat deceptive however. The gridded values Windsim has computed are quite coarse in resolution. Figure 23 shows the gridded output of Windsim, the plotted version is just a smoothed version.

The size limitation is clearly too restrictive to really test the accuracy of the model in Marmot Creek. For instance, in comparison to Mason and Sykes model, Windsim
does not predict any side effects of small ridges. The restricted number of cell affects the topography resolution. But it has also a deep impact on the calculations accuracy: Windsim might not be able to predict very complex wind regimes with only 6 cells layers between the ground and the top boundary. Nevertheless, the gridded results seem to be not absurd at all. Principal features are similar to Mason and Sykes one: high wind on ridges, low wind in creeks valley.

### 5.3.2 Comparison with met stations

Since the model is non linear, I have to compare the results in reference wind direction intervals and wind speed intervals. Figure 24 compares the measurements with DBSM and Windsim prediction for moderate and high wind speed. The reference wind direction is taken at Hay Meadow and corresponds to the upper boundary wind direction of Windsim. The station wind speed data were meant in a the 0-5 m/s and 5-10 m/s intervals. In order to compare the results, WindSim outputs were interpolated so that the mean wind speed at Hay Meadow fits with the meteorological dates.

![Figure 24: Windsim and DBSM prediction for moderate wind (~3 m/s in the valley) and strong wind (~6 m/s in the valley)](image)

Windsim with its large scale grid does not “see” any fine topography effects. Thus, the former graphs compare only wind speeds in typical large space configurations: a big mountain ridge (Nakiska Ridgetop), the valley bottom where topography effects are small (Hay Meadow).

Windsim and DBSM both predict negligible variations in wind speed with wind direction at Hay Meadow station. For Nakiska Ridgetop, there is much more to say. The station wind measurements do not follow a linear correlation with wind speed. Although DBSM seems to predict better in moderate wind regime, there is no way that its predicted curve fits with terrain data in high wind regime. Windsim underestimates
Table 2: Model quantified errors

<table>
<thead>
<tr>
<th></th>
<th>Mean error</th>
<th>Root mean square error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Windsim</td>
<td>DBSM</td>
</tr>
<tr>
<td>Moderate wind</td>
<td>1.3 m/s (17%)</td>
<td>0.6 m/s (9%)</td>
</tr>
<tr>
<td>Strong wind</td>
<td>3.2 m/s (21%)</td>
<td>4.2 m/s (28%)</td>
</tr>
</tbody>
</table>

the velocity in low wind regime. Nevertheless its estimation for high wind is a bit better then DBSM one. The prediction errors of the model are presented in table 2.

For the added computational costs, Windsim prediction is disappointing. However, we should keep in mind that the evaluation version was used and that the limited number of cells cannot render the entire amelioration provided by the 3D RANS solver and the $k - \epsilon$ turbulence model. Moreover strong wind regimes are the only one who contribute to blowing snow process. For instance, in figure 25, I have plotted the $\sum_{u_0 < u < u_0 + 1} u^4$ for 1 m/s intervals for Nakiska Ridgetop i.e. the blowing snow contribution of each wind speed. Moderate wind speeds under 10 m/s contribute for just 10% in blowing snow process.

![Figure 25: Blowing snow contribution of each wind speed (Nakiska Ridgetop Jan-May 2008)](image)

### 5.3.3 Predicted snow amount

Since Windsim is a non linear model, I have to discretize both wind direction and wind speed. I took the usual 45° direction intervals and the 2, 5, 7, 10 and 15 m/s wind speed. I made interpolations between this reference velocities to fit with wind speed given at the met station. I took also the “smoothed” wind maps and not the direct...
rough Windsim output. The new modified version of DBSM charges all these data on start. The wind dates use quite a lot of memory space (1Gbyte). I have run the model with Hay Meadow or Fisera Ridge met data from November 1 2007 to March 27 2008.

Figure 26: Windsim snow depth prediction (left), LiDar measurements (right) and DBSM prediction (bottom) on March 27 2008 (Fisera Ridge met file input)

Figure 26 shows that with Windsim model the blowing snow zone are much more spread then with DBSM because the model predicts larger zone of strong wind. In DBSM, strong wind areas are just concentrated on the top of ridges. Windsim results fits better with reality : LiDar measurements shows that this blowing snow redistribution occurs quite all over the alpine area. However, as I mentioned before, the wind prediction is not fine enough to recreate complex snow packs along small mountain
ridges. The size of snow accumulation on the tree line actually fits: ~2-3 m depth in both LiDar and Windsim (see Figure 27). The effects of vegetation are also more obvious with Windsim model.

Figure 27: Windsim snow depth prediction on March 27 2008 on the tree line (Fisera Ridge met file input)

6 A simple ridge

6.1 The problem

Figure 28: Spatial configuration and DBSM wind symmetric prediction at Fisera Ridge for a NW wind (equi-elevation are 5 m spaced, wind values for 1 m/s reference wind speed)

I have taken many snow surveys at Fisera Ridge. We always have to do snow measurements from the North Station to the South one. On the north side where the wind is
mostly coming from, it is always freezing with strong wind. On the other side, it is calmer with low wind. I was a bit disappointed to see that the linear DBSM could not predict that phenomenon (even if the reference station was Fisera Ridge itself), neither could the too rough and limited Windsim. Thus, I make a special study of this site in a two dimensional approach.

Mason and Sykes wind prediction is shown on Figure 28. This model evaluates high wind on the top of the ridge but no sensible difference between the two faces of the ridge. We could expect a kind of a flow recirculation on the down wind side. The wind might not always gently follows the topography! For instance, Figure 29 shows what could happen to a very sharp ridge.

Figure 29: Example of “aerodynamic stalling” and recirculation on a sharp 2D ridge (the arrows are air velocity vectors, uniform wind coming from left)

I choose to work with a two dimensional ridge in order to reduce computational time and to really control what is going on. There are actually three dimensional effects (venturi effects on pass, ...) I will miss. For Fisera ridge this assumption is, nevertheless, justifiable. The perpendicular transect to the ridge where the stations are located (see Figure 28) has a slope three times as steep as the slope parallel to the ridge. Thus, the side effects might be negligible in comparison with the main flow.

The configuration of Fisera Ridge perpendicular transect (SW-NW) is summed up in Figure 30. The three met stations are not exactly on the same transect in reality (see figure 28) but I interpolated with the distance to the ridge top.
6.2 Ansys 2D wind simulation

ANSYS FLOTRAN is a powerful finite element-based Computational Fluid Dynamics (CFD) analysis tool with steady-state or transient fluid flow. The fluid space is meshed into small boxes (Figure 31). I chose to have fine resolution on the ground (1 m) and rougher resolution for the top boundary (10 m). The whole ridge is around 500 m long. I prolonged the ridge with 100 m flat terrain on both sides. The boundary conditions were homogeneous wind (called later reference wind speed $u_0$) coming from the right on the right border, zero velocity on the ground, fixed pressure conditions for the rest of the boundaries. The viscosity and density of air were respectively $1.71 \times 10^{-5} \text{kg.m}^{-1}.\text{s}^{-1}$ and $1.34 \text{kg.m}^{-3}$ (values for -10°C and standard atmospheric pressure). Temperature is supposed to be constant and air is supposed to be incompressible.
Figure 31: Mesh used for simulations (1 m resolution on ground 10 m on the top boundary)

Since it is direct numerical simulation, it takes time to compute the results: about 1h for one simulation of 300 iterations.

Figure 32: Ansys computed wind prediction over Fisera Ridge
According to Figure 32, there are fewer differences than I expected between the upwind and downwind side of the ridge. The distribution of wind speed on top of the ridge is quite the same. Nevertheless, there is a “shadow” zone on the downwind side. It appears not directly after the top of ridge but on the bottom of it. Next to the ground, the shear stress is higher for the face directly exposed to the incoming wind.

Figure 33: Wind prediction over Fisera Ridge for different boundary wind speeds

In Figure 33, there are some results for the 2-m wind speed. The shapes of the curves are similar except above 6 m/s where the “shadow zone” appears at the bottom of the downwind face. The model behaves in a linear way next to the ridge.
Figure 34: Comparison of Ansys predictions and met stations measures

Figure 34 compares Ansys prediction with observations at the Fisera Ridge stations. The linear regressions were made in respect to the wind speed at the ridge top in 1m intervals. Since Ansys behaves linearly at the stations positions, we obtain a constant coefficient for the linear regression. The means scale fits with the measurements regressions but it does not reproduce the high variability with wind speed. For instance at the south face station, the wind speed is the same then at the top station for low wind regime (wind “following” topography) and it is twice as small as the top one in high wind regime (“shaded” zone). It is a bit disappointing that after all calculations, we still finally have a linear model! Mason and Sykes model would have shown the same results except for the small “shaded” zone.

6.3 The first FRBSM, the Fisera Ridge Blowing Snow Model

I kept the principle transport and sublimation equations given by SBSM and transformed DBSM in a distributed model for this 2D ridge. The Fisera Ridge Blowing Snow Model, FRBSM was born. The program loads the wind, the vegetation and the weather files at the beginning. It has a 1m resolution and a 15 min time step. It uses the discretized boundary wind speeds 2, 3, 4, 5, 6 and 7 m/s and makes small linear regressions between this values to have the real wind speed according to the ridge top station measurements. In my model, the wind is supposed to blow always from NW. Consequently, I considered that there is wind only when its direction is $315^\circ \pm 25^\circ$ (almost all wind).

I have mentioned questionable equations in section 2.2 because of a too small fetch. As a test, I have tried a more complex downwind transport distribution. The assumption steady-state flow across a 1m grid cell (i.e. $T_{in}(i) = T_{out}(i+1)$) is not necessarily
satisfied. Rather, the snow transport into a cell can be considered a function of the snow transport rate out of multiple upwind cells. I took the following square distribution:

$$T_{in}(i) = \sum_{i_s=0}^{n_s} T_{out}(i + i_s) * (n_s - i_s)^2 / \lambda$$

where $\lambda$ is just a normalization factor ($\lambda = \sum_{i_s=0}^{n_s} i_s^2$). $T_{in}$ is the incoming snow transport rate, $T_{out}$ is the outgoing snow transport rate, $n_s$ is the scale of how far you go upwind (in meter). The wind is blowing from the right.

Figure 35: Prediction of FRBSM for different distribution models

According to Figure 35, the basic distribution ($T_{in}(i) = T_{out}(i + 1)$) underestimates the amount of snow accumulation downwind. With this distribution, snow particles move only one metre per time step. With the square distribution, snow can directly “jump” over several cells and so move “faster”. Therefore, the results fit a bit better. Actually, $n_s$ depends on the time step. It should be tuned to fit reality. Using the square distribution we move the snow pack too far downwind. The snow surveys observations show that there might be snow accumulation next to the top of the ridge even if there is strong wind. This can be explained with the limited mass concentration of suspended snow. The air is saturated with snow and cannot blow anymore snow away.

7 Conclusions

DBSM’s original wind flow model based on Mason and Sykes theoretical work has shown some insufficiencies in attempting to model wind over alpine terrain. The mean
predicted scale of wind perturbation is acceptable but modelled strong wind is concentrated on only small areas, the ridge tops. This model might be sufficient to compute a local wind map around a reference met station. However, for large scale prediction, it mostly fails, especially for wind direction modelling.

The suggested alternative wind model, Windsim, provides respectable results in this complex mountain topography. Coupled with DBSM, it shows small improvements, compared to the original wind flow model, on snow distribution in Marmot Creek. Nevertheless, considering its computational cost, the improvements are not significant. However, the limited number of cells in the evaluation version is too coarse to predict complex wind regimes, which are affected by fine scale topographic configurations. Only the full version (1800€) could render the entire ameliorations provided by the RANS solver and the $k - \epsilon$ turbulence model.

The 2D approach with Ansys FLOTRAN provided the finest resolution for wind modelling. However, the non linear behaviour of the wind flow around a ridge is not sufficiently reproduced by the model. Low wind zones (called “shadow zones”) appear but not as close to the ridge top as the met stations observations exhibit. In mountain environment, a 2D approach remains a challenge! The precise wind prediction from FLOTRAN could be used in particular studies such as predicting snow accumulation on roads, under snow fences, etc. in the Prairies.

We will not be able to reproduce an accurate snow depth map using DBSM basis equations, regardless how accurate our wind map is. Firstly, the transport and sublimation equations based on the assumption of steady state flow on level terrain are difficult to justify and their limits have been shown on the particular case of a ridge. This has to be further developed. Secondly, it is a difficult to compare directly LiDar snow depth map with the predicted values where only blowing snow processes are modelled. Therefore, existing robust modules from CRHM should be added to DBSM (snowmelt, canopy interception, ...).

Acknowledgements

I wish to express my great appreciation to professor John Pomeroy of the Centre for Hydrology, University of Saskatchewan, for making this project possible and for his financial and material support. I would also like to thank Matt MacDonald and Logan Fang for answering several of my sudden questions. Also valuable was the company of Chris De Beer and Brad Williams during Kananaskis field trips.

References


Annexe : Development of the internship

- **15 April - 21 April**: field work in the Marmot Creek Basin. I stayed at the Kananaskis field station, Alberta (University of Calgary) to help graduate students from the Centre for Hydrology with snow surveys and stream gauging, thus learning about field work methods for snow hydrology and collecting data for my own project.

- **22 April - 24 April**: Western snow conference, Canmore, Alberta. I assisted to this conference to discover different approaches on snow hydrology.

- **4 May - 8 May**: field work

- **15 May - 19 May**: field work

- **1 June - 4 June**: field work

- **Rest of the time**: campus of the University of Saskatchewan, Saskatoon, focusing more especially on my project and the writing of this paper.