Towards a Geographical Information System of Snow Cover in Eastern Townships (Canada)

ROBIN FORTIER[1]

ABSTRACT

Mount Megantic area is unique in Eastern Townships (Quebec). It receives great amount of snow every winter. This mountain range is well known for its outdoor activities such as skiing, snowshoeing, hiking, hunting, fishing and for its water supply. Snow generates economic resources. Snow cover varies with topography and vegetation of the area and is highly diverse from one area to another. The objective of this research is to simulate point snow depth and to compare it to ground data. The methodology is to adapt meteorological data from Sherbrooke Meteorological Station to other locations using topography and vegetation into mass and energy balance or melt index equations. A simple algorithm was used to simulate hourly accumulation, compaction and melt. Field data was collected over two consecutive winters on Mount Megantic. The model was run for winter 2006-2007 and 2007-2008. Data from the first winter was used to calibrate the model. In conclusion, a simple algorithm may be used to estimate snow depth over the Eastern Townships in near real time.

Keywords: snow water equivalent, snow depth, Mount Megantic, snow cover, meteorological station

INTRODUCTION

Estimation of snow cover in highly variable terrain is difficult. Multiple factors interact with the snow cover. Selection of the most important factors is a challenge. The main hypothesis is that meteorological data from the station could be adapted using elevation, coverage of the ground (open, forest area). The objective is to simulate hourly snow depth throughout the winter using a laptop computer. Many models have been developed and used in multiple areas to represent snow cover. No perfect fit has been obtained from any model (Rutter *et al*., 2009).

Elevation is recognized as a factor for weather data. The air temperature and precipitation change with altitude (European Center for Median-range Weather Forecast 2008). Each precipitation of snow adds a layer to the existing snow cover. The compaction depends on the weight above each layer, temperature and time. The snow melt could be estimated differently in forest versus open zone. The air temperature is used to estimate snow melt in forest. In open zone it is more accurate to use mass, energy balance to follow snow cover evolution (Anderson, 1973, 1976). The algorithm described in this paper uses these principles to simulate the snow depth. Two winters operations 2006-2007 and 2007-2008 over Mount Megantic area in the Eastern Townships (Quebec, Canada) made it possible to collect the data (snow depth and water equivalent) to calibrate and validate the model.

[1] Sherbrooke University, 2500 blvd de l'Université, Sherbrooke, QC, J1K 2R1 Canada.

This is a first attempt to model snow cover in Eastern Townships. The basins of the area are connected to the quantity of snow on the Appalachian Mountains of the Megantic region. Water from these mountains is used as water supply for many towns in southern Quebec. It is interesting to demonstrate that a simple model using a laptop can be used to reproduce the thickness of snow on a territory at any time.

STUDY SITE

The study area lies between Sherbrooke and Mount Megantic. Several microclimates are present in this region. The low area of Mount Megantic (approximately 500 to 700 meters a.s.l.) is well representative of southern Quebec. At mid-mountain (elevation 700 to 900 meters) is the equivalent of mixed forests found in the north. The tops at 1000 meters are similar to the boreal forests of north Canada. Mount Megantic receives great quantity of precipitations in the Eastern Townships. The hot and wet air coming from the west condenses during its rise towards higher elevations. Clouds stay longer on Mount Megantic summit than the surrounding low areas. That fact could explain strong precipitations and thermal inversion of the mountain.

The area of study (Fig.. 1) is between 71 degrees 0 minute and 71 degrees 45 minutes of western longitude and between 45 degrees 15 minutes and 45 degrees 45 minutes of northern latitude is the area ranging between Mount Megantic in the east and Sherbrooke in the west; the American border in the south and Mount Stoke to the north. Altitude varies between 200 meters with 1100 meters of rise. The occupation of the territory is variable: it consists of urban areas, agricultural and forest. The urban and agricultural areas are located in the western sector of the zone of study. There are some rivers on the territory but few lakes. The sector of Mount Megantic is the highest elevation. It is also well-known for having the strongest precipitations. Various types of forest are present there: the leafy trees forest, the mixed forest and the evergreen forest.

Figure 1. Study Area.

DATA AND METHODS

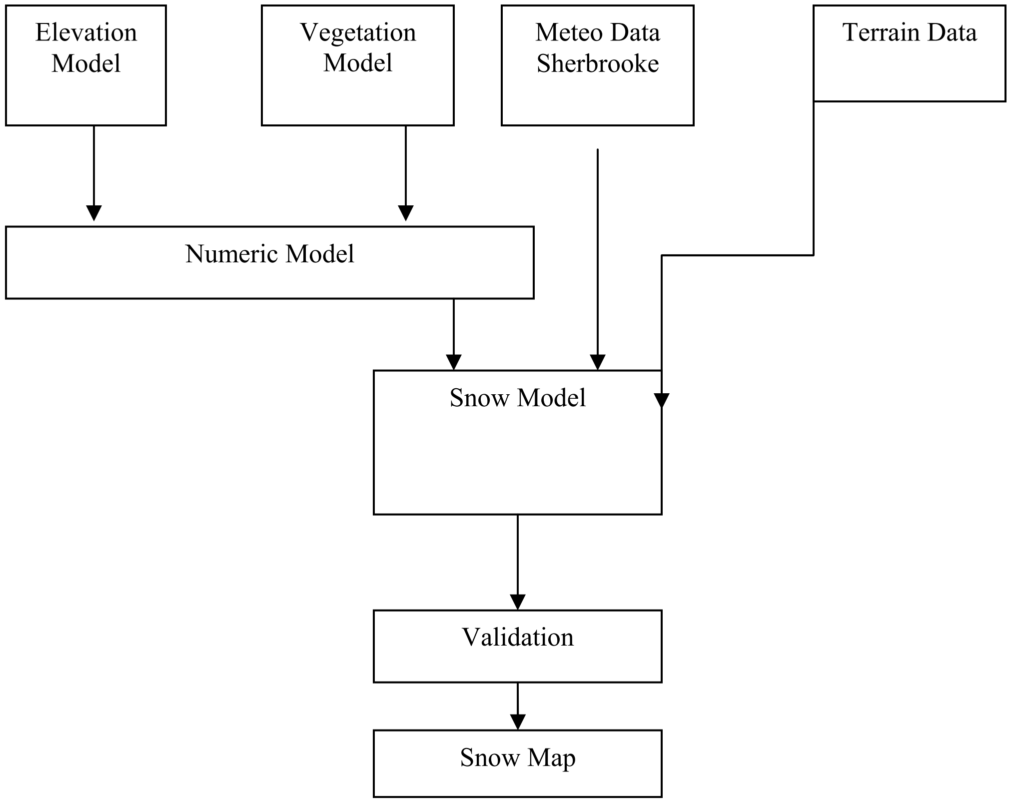

Figure 2. Methodology.

The study area is divided into grid cells of 30 meters by 30 meters. In the Elevation Model each cell gives elevation data and in the Vegetation Model it represents open or forest cover of the land. The elevation data used in the Elevation model is coming from Topographic Information Centre (Centre Information Topographique, 2003). The Forest Cover Information System gives the information for Vegetation Model (SIEF, 2003). Vegetation and Elevation grid cells information cover the same dimension and land area.

Weather data for air temperature, dew point, atmospheric pressure, wind speed, wind direction, quantity and type of precipitations for winters 2006-2007 and 2007-2008 was obtained from Sherbrooke Weather Station Environment Canada. The recording of long- and-short wave radiation data was done at Sherbrooke University Weather Station. The data from both meteorological stations was merged into a single database. The time step for this data is one hour.

The Snow Model described here is partly based on the S17 Snow Model (Anderson, 1973). S17 model only requires air temperature and precipitation. Additions to this model were done through considering energy balance in open terrain, melt index in forest, change in precipitation type, snow melt, air temperature and energy fluxes with the topography. Trees intercept snow, wind sublimates it and redistributes it (Liston *and* Sturm, 1998); these complex processes are not taken into account. Furthermore, the interactions between snow, the ground, the vegetation and snow are not modelled. This simplified model evaluates snow cover using multiple layers of snow (Fig.. 3). Each hourly precipitation is considered as a specific layer inside the snow cover.

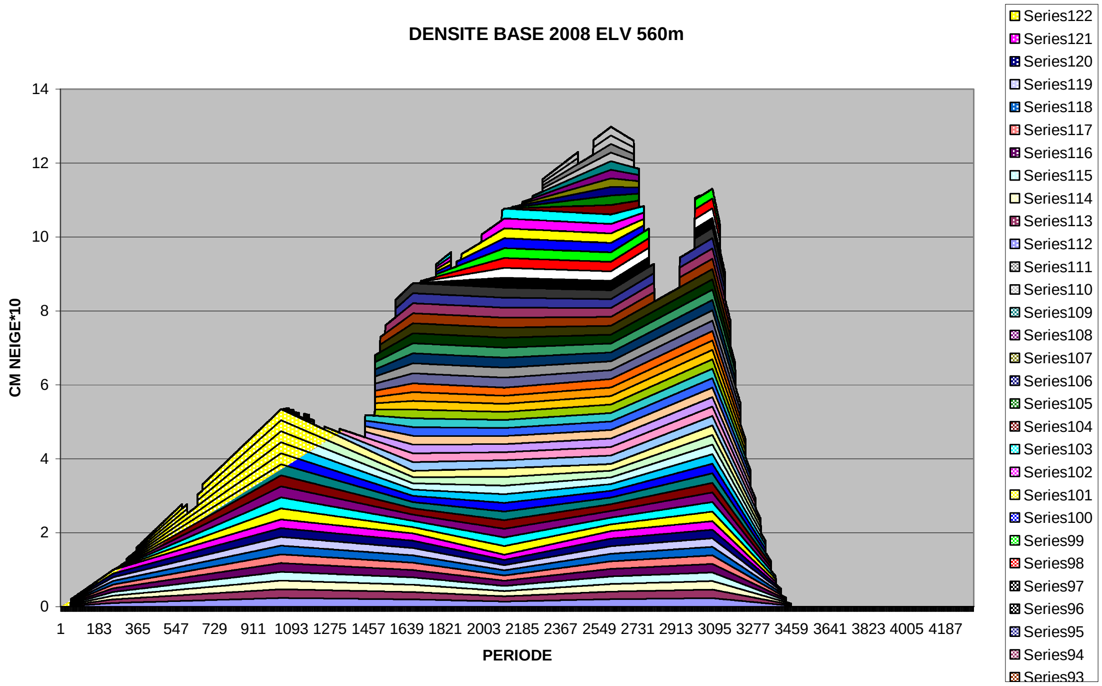

Figure 3. Multiple Layers Snow Cover.

This Snow Cover Model is adapted to represent a large territory. It combines mass, energy balance and melt index approaches to represent snow cover evolution on the territory. The energy approach is used in open terrain and the temperature one for forest areas. One should note that energy approach must be used in all terrain when rain precipitation occurs.

The energy approach asks for estimation of radiation, convection and conduction. Theses fluxes are very variable with topography.

The air temperature is not always adequate to represent the energy exchanges between the air and the ground. It is the case in open areas such as agriculture or lakes (Anderson, 1976): radiation and convection are important for better estimation of energy exchange between air and snow. For areas without vegetation, snow melt occurs through the energy exchanges of the wind and radiation (equation 1).

$$Qn + Qe + Qh + HQ + Qm = \Delta Q \quad (1)$$

Qn: radiative transfer Net (both short and long waves radiation)
Qe: latent heat transfer
Qh: convective heat transfer;
HQ: heat transfer interfaces ground-snow (not considered)
Qm: heat transfer by change of mass (effect of rain on snow cover)
ΔQ: change in the heat stored in the snowy coat

All fluxes change with ground topography. A ground having a south slope receives more short wave radiation. In a similar way, a slope against the winds receives stronger winds and a zone in the shade will have more radiation long waves. For example, radiation long waves will be larger in a concave zone, because the shade is more important. By cutting out the ground to be studied in several grids of 30 meters by 30 meters, it is possible to study the exposure to the wind and the radiation of the territory (Winstral and Marks, 2002).

Wind speed and radiation are estimated for each grid of ground on an hourly basis. Wind speed should follow this scenario: exposure to the dominant winds (western) is supposed to increase with the convex terrain, slope and elevation, but to decrease with the concave zones. Index of

Elevation, slope, westerly orientation, elevation difference against the prevailing wind and the difference between surrounding grids were developed (Granberg, 1973). To consider the influence of each factor on the speed of the winds, they should be multiplied.

The index of the exposure of the wind ranges between 0 and 1,3 for an altitude lower than 2000 meters (Garen *and* Marks, 2002). The speed of the winds for each grid of territory is estimated by reclassifying Sherbrooke wind speed to the wind range (0 to 1,3) using the index of exposure calculated above.

Similarly incoming short wave radiation measured in Sherbrooke is approximated for each parcel of territory with factors like slope, orientation. The incoming short wave radiation measured at the Sherbrooke University Weather Station is reclassified to value between zero and the value measured at the corresponding period using slope, orientation factor for the grid cell.

The reflection of short wave radiation (albedo) must be known to calculate the net radiation which penetrates in snow. A relation makes it possible to bind the size of the grains, the density of the layers of snow present on the points of study and the albedo of snow. A clean snow has an albedo in the neighborhood of 90%, a wet clean snow or in granules wet around 60% and one dirty snow near 30% (Gray *and* Male, 1981, p. 379).

As for the incoming long wave radiation one should consider the concavity of the ground to adjust Sherbrooke University Weather Station data to the grid cell as it supposes that the minimal value comes from measurements in open zone areas. The maximum value comes from the relation between the pressure vapor and the temperature of the air (Gray *and* Male, 1981, p. 383). The incoming long wave radiation is readjusted between minimum and maximum values using ground index for the chosen area. The net long wave radiation represents the incoming long wave radiation minus the reflected long wave radiation. The outgoing long wave radiation divided by the incoming is called the emissivity factor and it has been set to 0.99 in this study (Anderson, 1976).

In forest area during rain free periods, the model can be simplified by using air temperature to consider the exchanges *i.e.* the energy exchange between atmosphere and ground. A relation exists between temperature and altitude. This relation rises from the first law of thermodynamics is summarized by the following (equation 2):

$$dq = CpdT - \alpha dP + Ledw \qquad (2)$$

dq: added heat = 0 in this case
CP: capacity specific heat of the air
dT: change temperature of the air
α: specific volume
dP: change pressure
: latent heat
dw: change steam in the air

The air cools with elevation gain. Cooling continues with dry adiabatic until saturation of the steam in the air. The temperature decreases roughly by one degree Celsius for 100 meters in this zone. When the air rises beyond this zone condensation occurs and the temperature decreases by wet adiabatic process. The temperature decreases by 0.65 C for 100 meters roughly. The latent heat released by water condensation coming from saturated air slightly heats up the air **(**European Center for Median-range Weather Forecast, 2008).

Freezing air temperature is used as a threshold between rain or snow precipitation. However the quantity of precipitation varies. It is estimated that a relation exists between quantity of precipitation and altitude. The relation can be found by evaluating two or several points at different altitudes. Snow Water Equivalent measured at various elevation points is used as an indicator for precipitation. Snow density can be converted to precipitation assuming that snow precipitation has a density of 100 kg per square meter. A linear relationship has been built between elevation and precipitation. Snow accumulation is then known.

Ablation of snow cover in forest terrain is estimated with equation 2 when air temperature is above freezing.

MELT INDEX = (FF-NFF) * (Tair- Tbase) *RETENTION WATER

(3)

Tair: temperature of the air;
Tbase: temperature of snow cover in period of melt (zero degree C);
RETENTION WATER = Density water (kg/m3)/(thickness of snow (cm) *density of snow (kg/m3)) ;
FF = MELT FACTOR (#PÉRIODS 30 min converted into DAY) *∑ (snow precipitations in mm water)/(∑ DEW POINTS>0C);
NFF= DELAY MELT FACTOR=(#PÉRIODES 30 min converted into DAY) *∑ (precipitations of snow in mm water)/(∑ dewpoints < 0C);

The third stage is the estimate of the processes of transformation of snow cover.

In-depth layers of snow not having a contact with the atmosphere are subjected to the processes of energy exchange by conduction, described by the equation of Fourier (or equation 4) (Anderson, 1976). The crystals undergo a metamorphism and are compacted.

$$C_i * \rho S * \partial T/\partial t = K_e * \partial 2T/\partial z2 \qquad (4)$$

Ci: specific heat of the ice (cal/(gm*K))
ρ S: solid density of the portion of ice in snow-covered cover
T: temperature of snow in degree K
T: time in dryness
Z: outdistance interface air-snow in cm
Ke: effective thermal conductivity of snow in unit cal/(cm*K*sec))

Each hourly precipitation (snow layer) experiences an increase of density and a reduction in thickness. The equation of Kojima (equation 5) quantifies this process. These equations can be used for each layer. The principles of resolution are described in the literature (Anderson, 1976).

The compaction of layers of snow is calculated in equation 5.

$$1/\rho s * \Delta\rho s/\Delta t = Ws/\eta \qquad (5)$$

Ws is used as being the weight of snow over the layer for which the density switching is calculated and expressed in equivalent water value (cm), and **η** as being a constant known under the name of viscosity coefficient (cm/hour).

The snow depth of each layer is calculated. The addition of each snow layer gives snow depth at one grid point.

RESULTS

Figure. 4 represents snow depth simulations for winter 2006-2007 at three locations on Mount Megantic. These simulations were done with Melt Factor, Delay Melt and Precipitation Factor coming from winter 2006-2007.

The beginning and end of season are more difficult to represent the snow depth adequately. Indeed when the air temperature is close to freezing point the division of precipitations between rain and snow becomes more difficult. This is often the case at the beginning and the end of the season.

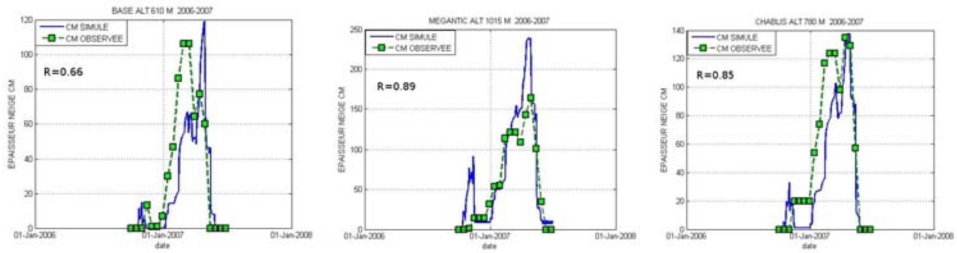

Figure 4. Snow depth simulated (blue) versus real (green) Mount Megantic area winter 2006-2007.

Figure. 5 represents snow depth simulations for winter 2007-2008 at three positions on Mount Megantic.

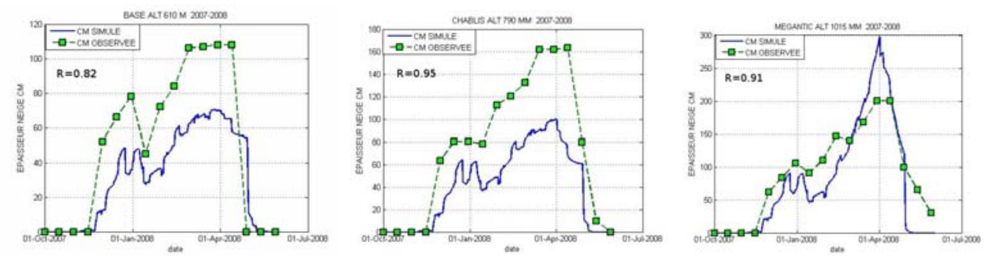

Figure 5. Snow depth simulated (blue) versus real (green) Mount Megantic area winter 2007-2008.

CONCLUSION

This simple Snow Model simulates the thickness of snow in the Eastern Townships area using Sherbrooke Weather Station and considering topography and vegetation. Accumulation and melt of snow for each grid cell is considered. Relationships between elevation and precipitation, air temperature are used. Melting of snow cover follows various scenarios. Energy balance is used in open area or any grid in rain event, index temperature in forest zone for rain-free period.

The air temperature and other energy fluxes are estimated for each grid of territory using the theoretical equations. The temperature estimated with theoretical relationships is often different from the field reality. Thermal inversions are frequent in mountain environment. It may be difficult in splitting precipitation to rain or snow. The inaccurate estimates of precipitations are frequent when the air temperature is close to freezing point. This snow model could call for snow when it rain. Precipitation occurs mainly in beginning and end of season, the snowfalls are over-estimated during these periods. In general a meteorological station can be used to represent the snow depth of the surrounding area. However, adjustments would be necessary to improve the precision of the estimate calculations of snow depth. Improvements at the main entries of the model (temperature, precipitation) would help simulations.

Also, it is not clear that estimation of other processes such as snow transport, snow interception by vegetation, sublimation, ground absorption, follow-up of liquid water and the steam in the snow cover and albedo change would improve the existing model.

This model is a first step towards the construction of Global Snow Model using simple existing computers. This model can be extrapolated worldwide by using several weather stations and ground data available. It can also be merged into RCM and GCM climatic models. Satellite images could be used to validate snow cover where few Meteorological Stations are available in remote areas (Arctic and Antarctic).

REFERENCES

Anderson, E.A. 1973. Snow accumulation and ablation model. NOAA tech. Memo. NWS HYDRO-17, 217 p.

Anderson, EA. 1976. A point energy and mass balance model of a snow cover, NOAA technical report NWS19, 150 p.

Centre Information Topographique 2003.Données numérique élévation du Canada, Sherbrooke (Canada), http://www.geobase.ca/geobase/fr/data/cded/index.html

European Center for Median-range Weather Forecast 2008. Numerical Weather Prediction Parametrization of diabatic processes. Reading, England. www.ecmwf.int/newsevents/raining/meteorological_presentations/ppt/PA/moist_intro.ppt

Garen, DC. Marks, D. 2005. Spatially distributed energy balance snowmelt modelling in a mountainous river basin: estimation of meteorological inputs and verification of models results. *Journal of Hydrology* **35**: 126-153.

Granberg, HB. 1973. Indirect Mapping of the Snow Cover for Permafrost Prediction at Schefferville, Quebec. *Proceedings: Second International Conference on Permafrost, Washington, D.C., National Academy of Sciences***.** 113-120.

Gray, DM. and Male, DH. 1981. Snowcover ablation and runoff. Chap. 9, p. 360-436. *in* Gray, DM and Male, DH (réd.) (1981) *Handbook of Snow*. Wiley, New York, 776 p.

Liston, G. and Sturm, M. 1998. A snow transport model for complex terrain. *Journal of Glaciology* **44**:148: 498-515.

Rutter, N. Essery, R. Pomeroy, J. Altimir, N. Andreadis, K. Baker, I., Barr, A. Bartlett, P. Boone, A. Deng, H. Douville, H. Dultra, E. Elder, K. Ellis, C. Feng, X. Gelfan, A. Goodbody, A. Gusev, Y. Gustafsson, D. Hellstrom, R. Hirabayashi, Y. Hirota, T. Jonas, T., Koren, V. Kuragina, A. Lettenmaier, D. Li, W-P. Luce, C. Martin, E. Nasonova, O. Pumpanen, J. Pyles, R.D. Samuelsson, P, Sandells, M. Schadler, G. Shmakin, A. Smimova, TG. Stahli, M. Stockli, R. Strasser, U. Su, H. Suzuki, K. Takata, K. Tanaka, K. Thompson, E. Vesala, T. Viterbo, P. Wiltshire, A. Xia, K. Xue, Y. Yamazaki, T. (2009) Evaluation of forest snow processes models (SnowMIP2). *Journal of Geophysical research* **114**: D06111.

SIEF: Système Information Écoforestière 2003. Ministère des ressources naturelles. Charlesbourg, Québec, Canada. www.collections.banq.qc.ca/ark:/52327/44232

Winstral, A. and Marks, M. 2002. Simulating wind field and snow redistribution using terrain based parameters to model snow accumulation and melt over semi-arid mountain catchments. *Hydrological Processes* **16**: 3585-3603.