The Distribution and Properties and Role of Snow Cover in the Open Tundra

ANDREW REES[1], MICHEAL ENGLISH[1], CHRIS DERKSEN[2], AND ARVIDS SILIS[2]

ABSTRACT

The spatial distribution and temporal dynamics of arctic and sub-arctic snow cover have a direct influence on regional and hemispheric energy balance, carbon cycling, hydrological storage and ecological dynamics. Snow cover information from both manual in-situ and gauge measurements have been gathered in many regions throughout Northern Canada over a long time period, yet there is a general lack of both spatial and temporal continuity within these data sets. In Canada, daily snow depth observations are available from 1955 to present for most stations and from 1915 to present for some stations. Unfortunately, most, if not all, long term snow monitoring stations are located south of 55°N despite the abundance and dominance of a northern snow cover (Brown, 1997). The lack of northern snow data is directly a result of sparse human population combined with a lack of automated stations and the logistical difficulties associated with obtaining data in remote regions.

The purpose of this research is to develop a more complete understanding of open tundra snow cover properties and distribution for application to hydrological modeling, evaluation of climate model simulations, and the development and validation of regional satellite passive microwave snow water equivalent (SWE) algorithms. Of specific importance are 1) the characteristics of open tundra terrain and its control on snow catchment and wind re-distribution, 2) the variability of snow depth, density and SWE within and between different terrain units, and, 3) the applicability of in-situ snow cover data to large scale modeling.

SNOW COVER DATA

Snow cover data were obtained during intensive field campaigns in a 625 km^2 portion of the Daring-Exeter-Yamba river basin from 2003 to 2007. This research project has generated a five year snow cover dataset that is one of the most comprehensive compiled over a Canadian open tundra environment. During these campaigns over 30 000 depth measurements were made using a snow probe and 5 000 snow cores for density and SWE estimation were taken. The samples were obtained at sites in an area defined by one 25 x 25 km satellite passive microwave grid cell and other at other sites throughout the basin.

It has been recognized by many researchers that the patterns of tundra snow cover distribution are largely a product of wind re-distribution and complex snow-terrain interfaces (Essery and Pomeroy, 2004, Hirashima et al., 2004, Liston, 2004, Sturm and Liston, 2003). The snow cover throughout the study area was found to be very heterogeneous both at a site scale and between different landscape types. Snow redistributed by varying wind speed and direction interact with micro and macro topography, frozen lake surfaces, grassy tussocks, boulder outcrops, dwarf birch

[1] Cold Regions Research Center, Department of Geography, Wilfrid Laurier University, Waterloo, Ontario N2L 3C5, Canada – rees2141@wlu.ca
[2] Climate Research Branch, Meteorological Service of Canada, Downsview, Ontario, Canada

and small coniferous trees to produce highly variable snow cover patterns. For the purpose of relating this complex snow cover information to large scale models or simulations it is important to somehow quantify variability at a sub-grid scale.

More regionally uniform landscapes, such as, lakes and flat tundra tend to be much less variable both within individual sites and when comparing similar sites. Lake sites were found to have the least regional variability in snow depth and SWE within survey years and even showed some similarities between years (see Figure 1). At a local scale, however, some lake sites have a much higher degree of heterogeneity. Smaller lakes, ponds or edges of large lakes can have sections where the wind has completely removed the snow cover and exposed bare ice. Sites of this nature tend to be more localized, and depend on how the surrounding topography redirects and controls wind patterns.

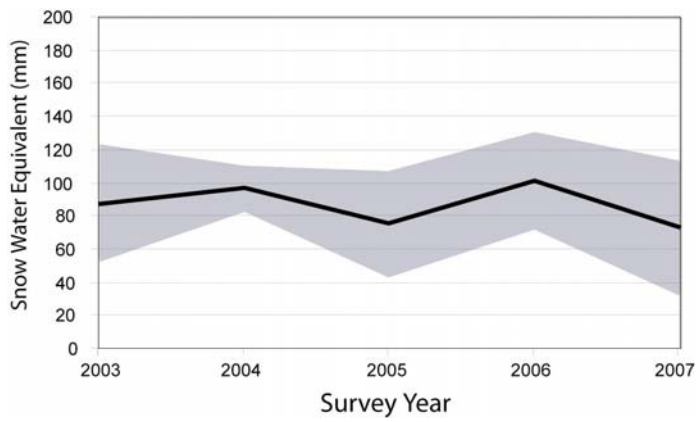

Figure 1. The variability in snow water equivalent on Lakes observed during pre-melt snow surveys conducted in April 2003, 2004, 2005, 2006 and 2007. The mean is shown by the dark black line. The grey area illustrates plus and minus one standard deviation.

Flat tundra sites are the most homogenous of the terrestrial environment. Flat tundra snow depth and SWE are more variable than on lakes, as a result of the dynamics of snow-vegetation interaction. Thus, the added complexity of snow on flat sites depends in large part on the type of vegetation present. For example, on open grassy plains, the standard deviation of SWE can be as low as 10 percent. On sites where larger and emergent vegetation is present the standard deviation can be as high as 75 percent. The combination of such sites across the landscape produces standard deviations in the range of 20 to 50 percent, depending on survey year (see Figure 2).

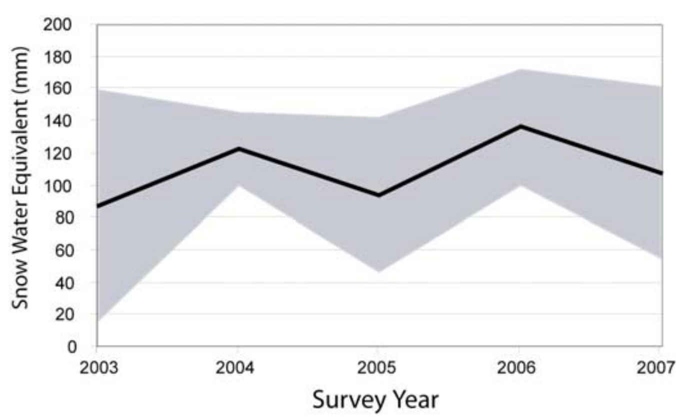

Figure 2. The variability in snow water equivalent on flat tundra observed during pre-melt snow surveys conducted in April 2003, 2004, 2005, 2006 and 2007. The mean is shown by the dark black line. The grey area illustrates plus and minus one standard deviation.

Sites located on slopes are consistently the most variable in the tundra environment. Topography exerts a strong control on snow deposition in a tundra environment (Pomeroy et al, 1997). Snow deposition on slopes depends on many factors that are difficult to isolate and quantify over large basins. For the purposes of simplicity in making field observations, slope angle and aspect were the two main categories used to subdivide slope types. Generally there was less snow accumulation and higher variability on slopes of a lower angle (less than 7 degrees) than on steeper slopes. The higher variability on lower slopes occurs because lower snow depth results in more interaction with sub-surface features, such as micro-topography, boulders and vegetation. Accumulation patterns on steeper slopes are more a factor of slope aspect. Significant snow accumulations were present in each survey year but the aspect of depositional slopes varied depending on annual wind patterns (see Figures 3 and 4).

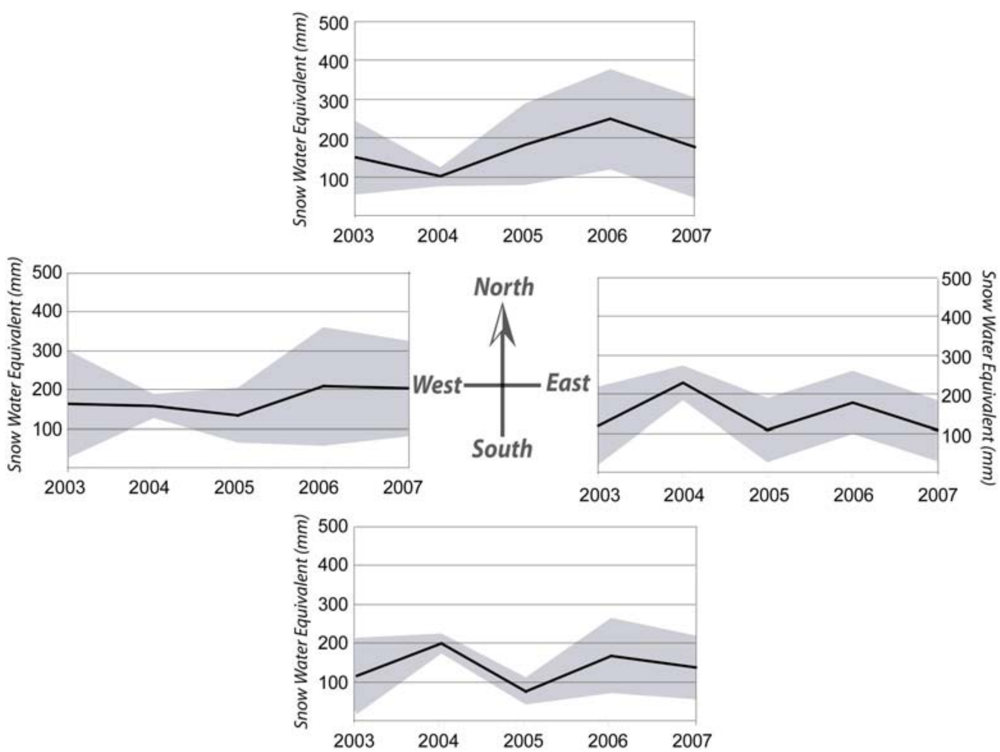

Figure 3. The variability in snow water equivalent on slopes of various aspects, with a slope angle of less than 7 degrees, observed during pre-melt snow surveys conducted in April 2003, 2004, 2005, 2006 and 2007. The mean is shown by the dark black line. The grey area illustrates plus and minus one standard deviation.

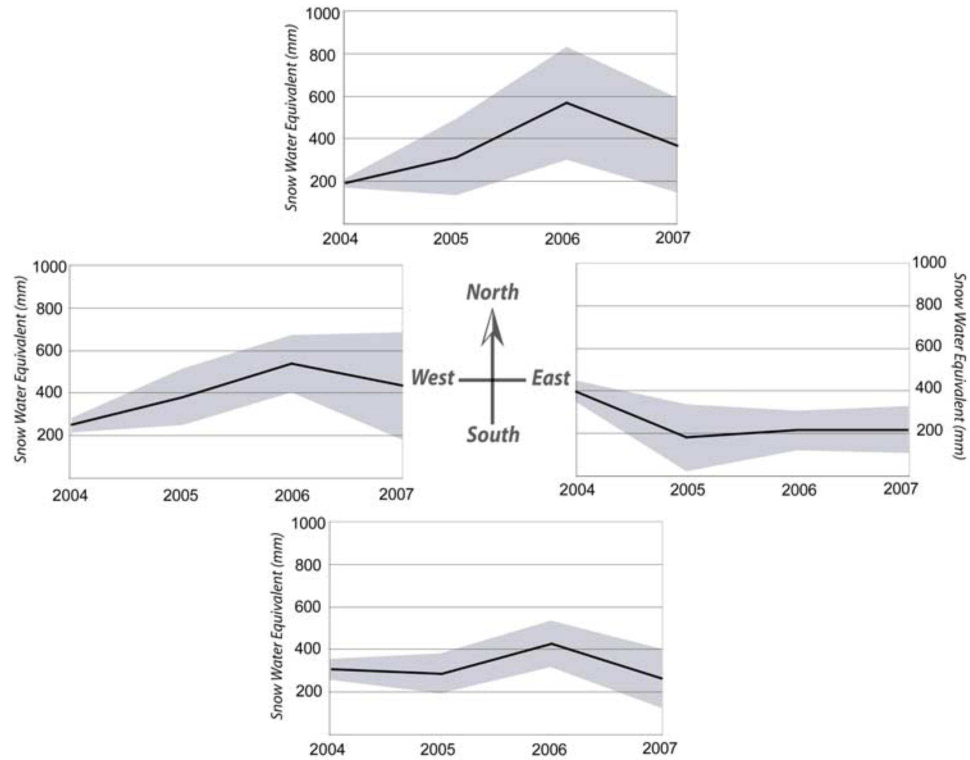

Figure 4. The variability in snow water equivalent on slopes of various aspects, with a slope angle of greater than 7 degrees, observed during pre-melt snow surveys conducted in April 2003, 2004, 2005, 2006 and 2007. The mean is shown by the dark black line. The grey area illustrates plus and minus one standard deviation.

INTER-ANNUAL COMPARISON

Using these data it is possible to begin to understand some of the inter-annual variability and seasonal dynamics of snow on the tundra. Figures 1, 2 and 3 show the change in SWE from year to year over lakes, flat tundra and slopes. Snow density on these features does vary somewhat year to year but overall is more consistent than depth. This further reinforces earlier research which found that a regional density value can be applied so that snow depth can be a used as a proxy for SWE (Rees et al., 2005). Seasonal variability in density is dependant on the magnitude and direction of wind, and the timing of high wind speed event relative to snowfall events. This relationship, although apparent from anecdotal evidence, is difficult to quantify in remote regions without including detailed weather observations.

SWE may seem quite different from year to year but certain inter-annual similarities exist. Flat tundra is the most spatially expansive and easily characterized feature on the tundra landscape. Therefore, the ratio of SWE on flat tundra to SWE on other landscape types could be useful for characterizing inter-annual similarities.

The ratios of SWE on flat tundra to lakes and upland plateaus are very consistent for the study years compared (see Figure 5). This indicates that despite differences in SWE from year to year, the SWE on lakes is consistently 65 to 75% less than on flat tundra. Similarly, SWE on upland plateaus is consistently 45 to 55% less than on flat tundra.

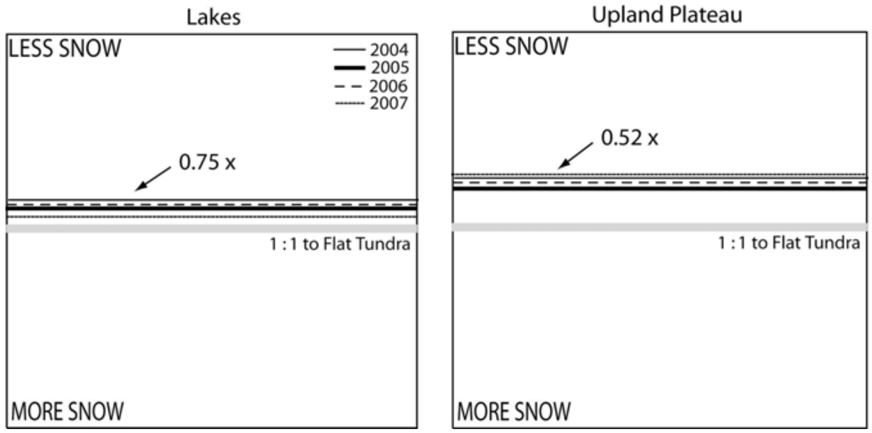

Figure 5. The ratio of SWE on lakes and upland plateaus to flat tundra between the 2004, 2005, 2006 and 2007 field seasons.

Slope areas are a little less consistent as the deposition of snow on slopes depends largely on dominant wind magnitude and direction during and following snowfall events when an unconsolidated surface layer of fresh snow is available for redistribution. However, slopes consistently contain more snow than flat areas. On the dominant depositional slope features, which have different slope aspects year to year, there is consistently 3 to 4 times more SWE than on flat tundra (see Figure 6).

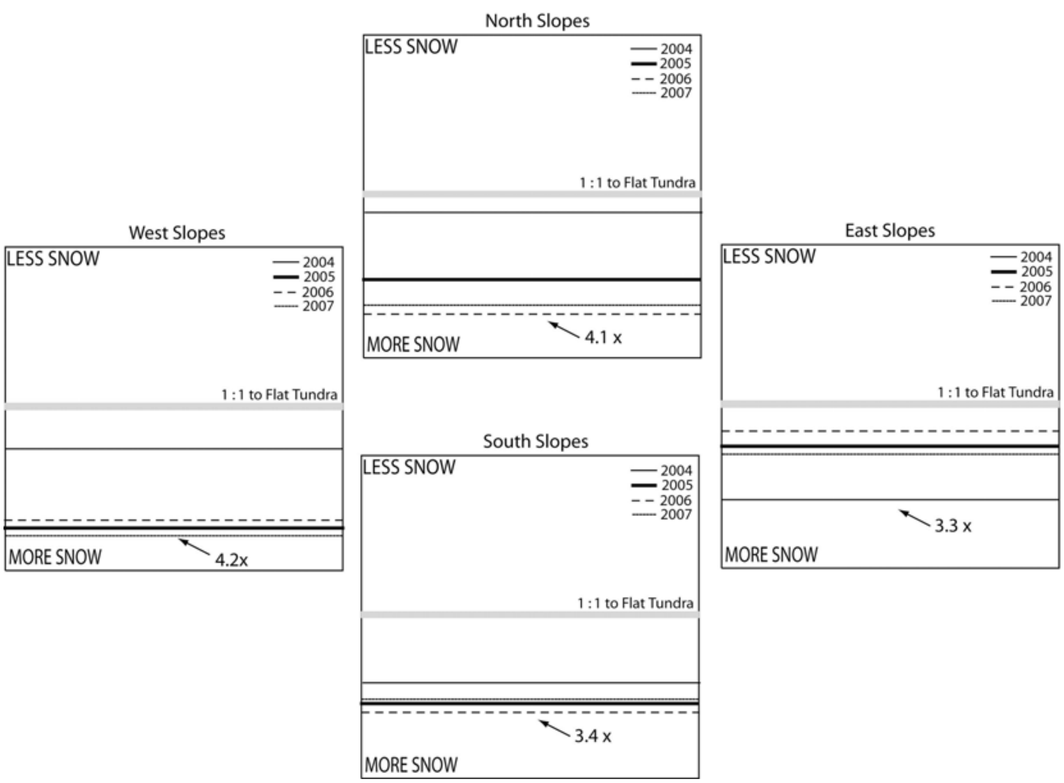

Figure 6.The ratio of SWE on slopes of various aspect (north, east, west and south) to flat tundra between the 2004, 2005, 2006, and 2007 field seasons.

Examining the ratios of SWE from flat tundra to other landscape features is a very useful way to characterize the differences and consistencies in inter-annual tundra snow cover. If the ratios between certain features are consistent from year to year (ie lakes) then it becomes much easier to extrapolate spatially constrained snow survey data over larger regions. Similarly, if remotely acquired data from meteorological stations or satellite sources can provide some estimate of snow on flat tundra then it would be possible, using these ratios, to extrapolate and estimate regional snow cover distribution.

RELATING SNOW COVER DATA TO LARGE SCALE REMOTE SENSING ESTIMATES

Relating variable tundra snow cover to large scale model outputs is certainly a challenging task. Coarse resolution satellite passive microwave SWE retrieval algorithms provide a single estimate of SWE over a 625 km^2 area. An average in-situ SWE value for the same area, using a terrain classification approach, can have a standard deviation as high as 100%. Current passive microwave algorithms significantly underestimate SWE in the open tundra due to a number of confounding factors (Rees et al., 2006). However, even if the satellite algorithms could provide the same SWE as derived from an in-situ average, how representative would this value be of tundra snow cover given the extreme sub-grid variability?

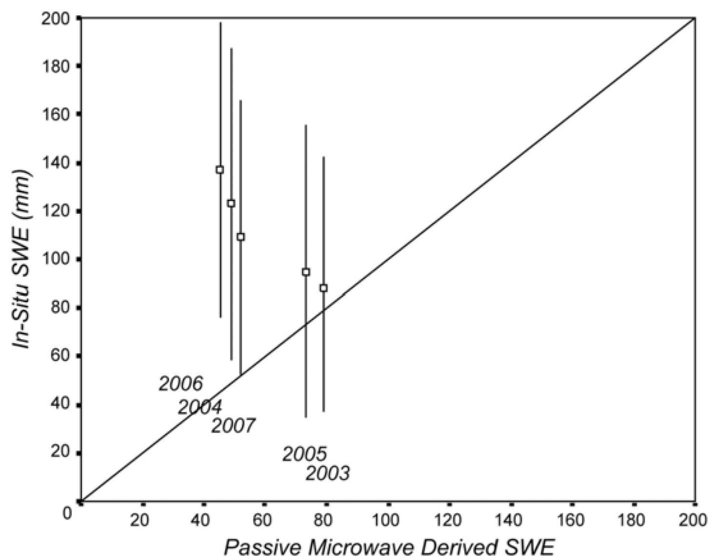

Figure 7. Passive microwave estimated SWE, using the current Environment Canada open ground algorithm, against in-situ measured SWE derived for the 2003 through 2007 snow surveys using the aforementioned terrain classification.

The boxes seen in Figure 7 represent the relationship between mean in-situ SWE and the algorithm derived SWE. The vertical lines represent the standard deviation of in-situ SWE. The degree of underestimation is evident when comparing the average in-situ to the satellite estimate. However, there are a great number of in-situ values that fall close to, directly correspond to and even fall below to the satellite estimate. Thus, the value of such satellite estimates relies on the characteristics of the data set used for development and validation. As such, a more complete understanding of tundra snow cover distribution, properties and natural variability is a necessary precursor to satellite algorithm and other large scale model development and validation.

REFERENCES

Brown, R. D. 1997. Historical variability in Northern Hemisphere spring snow-covered area. Annals of Glaciology. **25**: 340-346.

Essery R, and J Pomeroy. 2004. Vegetation and Topographic Control of Wind-Blown Snow Distributions in Distributed and Aggregated Simulations for an Arctic Tundra Basin. Journal of Hydrometeorology **5**: 735-744.

Hirashima H et al., 2004. Nonuniform Distribution of Tundra Snow Cover in Eastern Siberia. Journal of Hydrometeorology **5**: 373-389.

Liston, G E. 2004. Representing Subgrid Snow Cover Heterogeneities in Regional and Global Models. Journal of Climate **17**: 1381-1397.

Pomeroy, J. W., P. Marsh, and D. M. Gray. 1997. Application of a Distributed Blowing Snow Model to the Arctic. Hydrological Processs. **11**: 1451-1464.

Sturm M, Liston G. 2003. The Snow Cover on Lakes of the Arctic Coastal Plain of Alaska, U.S.A. Journal of Glaciology, **49**: 370-380.

Rees A et al., 2005. Assessing Snowpack Water Equivalent Distribution in an Open Tundra Environment Using Various Scales of Passive Microwave Data. In Proceedings, 62nd Eastern Snow Conference, June 2005, Waterloo ON.

Rees A et al., 2006. Uncertainty in Snow Mass Retrievals from Passive Microwave Sensor Data in Lake-Rich High Latitude Environments. *Hydrological Processes (HP Today)* ***20****. 1019-102.*