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Pixel-Scale Ground Snow Survey for Passive Microwave Study of the Arctic Snow Cover

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ABSTRACT

Field data on regional snow distribution is needed to aid in the development of algorithms for remote sensing surveillance of snow cover variation in the Arctic. An extensive snow survey was conducted in May 1994, in central Ellesmere Island. The results confirmed the significant role of topography in controlling the snow distribution, with the snow water equivalent being the greatest in gullies and valleys and the lowest on exposed terrain such as wetlands, flat valley floors or rolling uplands. During the survey period, Special Sensor Microwave Imager (SSM/I) passive microwave satellite data (brightness temperatures) were acquired for the study area, with each SSM/I pixel covering about 150 km^2, and the microwave brightness temperature representing an integration of a variety of ground snow conditions. The field survey data were areally weighted according to the terrain components and the ground snow conditions thus obtained were compared against the microwave brightness temperatures for two test pixels. The general trends exhibited by the satellite and the field data were comparable. The field technique is superior to other existing approaches for regional snow survey and warrants repeated application in the Arctic Islands to enable quantification of satellite information under a broad range of snow conditions.

Keywords: snow cover distribution, microwave remote sensing, snow survey, Arctic, snow water equivalent.

INTRODUCTION

With increasing emphasis on regional hydrologic and climatic modelling (e.g. GCM, GEWEX), there is a growing need for snow information on a regional scale. Satellite observations, notably passive microwave information, are suitable for regional models, but ground-based snow cover data for validation of such information is not available in the Arctic. Conventional snow surveys gather data from single points or from clusters of points. The scale at which these data are collected is incompatible with the pixel size of satellite imagery and cannot be used for mapping snow distribution over large areas. There is a need to develop a field technique to obtain information on a scale that is compatible with regional mapping and modelling. This paper describes one such snow survey method for the Arctic Islands of Canada where the terrain is the major factor that governs the snow distribution on the ground. The purposes of the paper are (1) to present the proposed method for regional snow survey, (2) to show the sub-pixel variability of snow distribution and (3) to compare the snow survey result with microwave brightness temperatures obtained by Special Sensor Microwave Imager.

STUDY AREA AND METHODS

This study covered a five day period in May 1994. Fosheim Peninsula, Ellesmere Island, N.W.T., in the Canadian High Arctic was chosen as the study area because it has been designated as the Global Change Observatory of the Geological Survey of Canada and it

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includes the Eureka weather station which provides long-term climatic data and a logistical base for field work. The traverse covered an area of about 300 km^2, roughly along 80° N. In selecting the traverse, care was taken to avoid large water bodies (sea and large lakes) and ice features (glaciers, sea and lake ice) to ensure that the snow alone exerts the dominant effect on the passive microwave signals.

Field Methods

Previous study of the Eureka area showed that the snow distribution at the end of winter is strongly influenced by the terrain because of prolonged snow drifting during the winter months (Woo et al. 1983). Eight major terrain types are recognised for the target area, including plateau, rolling upland, wetlands and ponds, lakes, flat valley floors, valleys, gullies and long slopes of various aspects. In addition, a thermokarst area was identified, with depressions and rough surfaces that cause considerable snow redistribution within this terrain type. A terrain map was produced from aerial photographs to guide the snow survey in the field.

The snow survey was carried out by two persons on snow-mobiles. In the field where the snow cover rendered most landscape features hard to recognize, the transect lines were located using a combination of Global Positioning System and aerial photographs. The various transects covering the target area are shown in Figure 1. The length of a transect varied from tens of metres to several kilometres, depending on the type of terrain. A typical transect is a straight line across the terrain, with samples of snow depth taken at regular intervals. Snow density is measured at the beginning and end of the transect and at selected points in-between. To avoid bias, the snow-mobiles stopped at approximately equal distances, depending on the scale of the feature. For example, the interval between consecutive stops on a valley transect may be 10 m, but for a transect across the rolling upland, the distance between each stop may be 30 m. At each stop, four snow depth measurements were taken as the surveyors walked to the corners of a 10-metre square. This is to avoid taking single extremely deep or extremely shallow values to represent one particular site.

A total of 48 transects were employed, each yielding 8 to 40 snow depths and 2 to 5 snow densities. Depth was measured by plunging a steel rod or a steel ruler into the snow until solid ground was encountered. Density was determined using a Meteorological Service of Canada snow sampler.

Satellite Data

The use of passive microwave satellite data to derive snowcover properties at global, national and regional scales has been actively developed and tested by several research groups (Chang et al., 1987; Goodison, 1989; Hallikainen and Jolma, 1986). In Canada, algorithms have been developed and validated for the determination of snow water equivalent for the prairie region of western Canada (Goodison, 1989). The field surveys conducted at Fosheim Peninsula support research into the potential use of passive microwave data for the determination of snow cover information for Arctic regions.

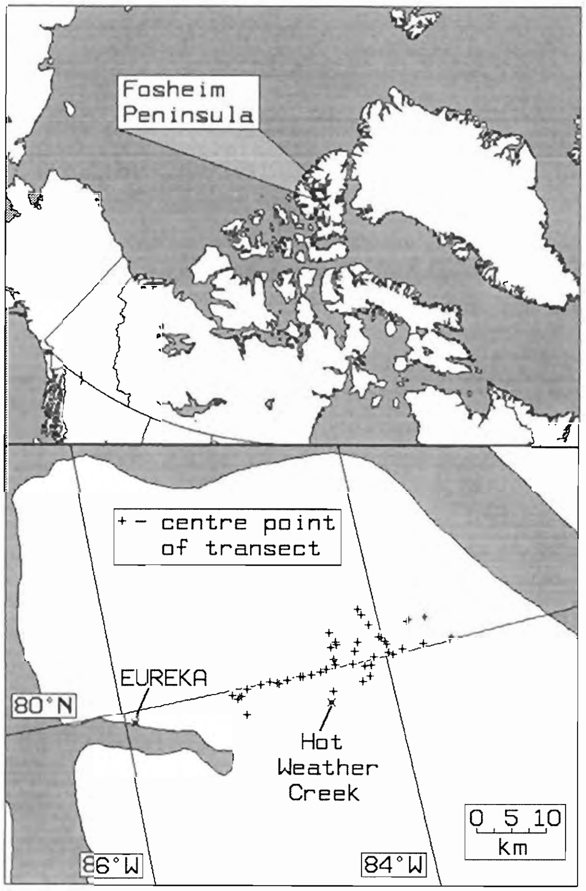

Figure 1: Fosheim Peninsula, Ellesmere Island, and the locations of the snow survey transects sampled during the May 1994 field study.

Passive microwave satellite data from the Special Sensor Microwave Imager (SSM/I) on the U.S. Defense Meteorological Satellite Program (DMSP) F-11 satellite were acquired daily throughout the May 1994 snow survey period for orbital passes with coverage of Fosheim Peninsula. The SSM/I is a seven channel passive microwave radiometer which measures microwave emission from the earth's surface at four frequencies: 19.35, 22.235, 37.0 and 85.5 GHz. Since the Fosheim Peninsula is only 75 km wide, brightness temperature data from the 85 GHz channels (horizontal and vertical polarization) were used because its spatial resolution is the finest of all the SSM/I frequencies. The field of view on the earth's surface of an 85 GHz pixel is a 13 km x 15 km ellipse. Also, as 85 GHz is the highest frequency of all the SSM/I channels it should be more sensitive to shallow snow covers typical of the high latitudes.

SNOW DEPTH AND DENSITY

The snow survey data approximated the total snow accumulation over the region for the period between September 1993 and the end of April 1994. In view of the low temperatures and the absence of incoming radiation during several winter months, it is reasonable to assume that only a small amount of melting took place during the winter, an amount that is well within the error limit of the snow survey. Although the areally determined snow cover data cannot be compared directly with single site measurements made at the Eureka weather station, the station snow data provide an indication of the snowfall variability over a period of years. The station makes daily measurements of snowfall precipitation and conducts a bi-monthly ten-point snow survey to measure snow water equivalent. Compared with the long-term mean snowfall precipitation of 34 mm, the 22.2 mm winter total for 1993-94 was very low.

Our snow survey results confirmed that the Fosheim snow cover was shallow, with most of the snow drifted into sheltered areas such as gullies or valleys. Pooling the data for various terrain types, *regardless of location*, depth (values given in mm) was the greatest in gullies (497 ± 129), the thermokarst zone (298), followed by the valleys (201 ± 36). The snow was shallower on exposed terrain, including the flat valley floors (141 ± 29), wetlands and lakes (154 ± 47), rolling uplands (163 ± 34) and plateaus (173 ± 16). Depth on slopes was highly variable, with deeper snow on north (311 ± 88) and northwest (295) slopes, followed by the south (184 ± 65), southeast (166), west (162 ± 14) and then the east (153) slopes. Transects with deeper snow tended to be more variable in depth, as was shown by the larger standard deviations associated with greater depths (Table 1).

There was a weak relationship between snow depth and snow density (r^2=0.26, based on 88 samples) but the scatter was considerable. Stratigraphic sections suggested that the mixture of compacted, wind-blown snow with fresh snowfall increased the variability of the overall snow density for the snow column so that individual observations could vary from under 200 to over 400 kg/m^3. Taken as averages for each terrain type, however, the mean densities were around 250 to 340 kg/m^3.

The snow water equivalent (w in mm) for each terrain type j was calculated by

$$w_j = \rho_j d_j$$

where ρ and d are snow density and snow depth. The calculated snow water equivalent (Table 1) indicated a pattern similar to that of snow depth, with the sheltered areas having more snow (w values of 153 mm for gullies and 102 for the thermokarst zone). Less snow accumulated in the valleys (56 mm), the plateaus (51 mm), the wetlands and lakes (49 mm). Rolling upland (46 mm) and flat valley floors (43 mm) had the least amount of snow. Depending on exposure to snow drift, the water equivalent on slopes was variable, yielding higher values on north (92 mm) and northwest (95 mm) slopes, followed by south slopes (62 mm), but was much less on the west (46 mm), east (38 mm) and southeast (40 mm) slopes.

There was a difference in the snow conditions between the eastern and the western parts of Fosheim Peninsula, at least for certain types of terrain. Splitting the snow survey data into two subsets, the snow water equivalent for the rolling uplands east of Hot Weather Creek was 51 mm and it was 33 mm for the uplands west of the Creek. Similarly, the plateaus east of the Creek had 59 mm of snow, but only 42 mm on the western plateaus.

PIXEL SNOW DISTRIBUTION

Mean snow water equivalent

Over the Fosheim study area, each SSM/I 85 GHz pixel is an integration of a large variety of snow conditions on the ground. The influence of vegetation is negligible as it is completely buried by the snow. To obtain an areally weighted snow water equivalent for an area covered by a pixel, the mean snow water equivalent for each terrain type is weighted by the area covered by that terrain. For a pixel that includes n types of terrains, the weighted mean snow value W_p is

$$W_p = \sum_{j=1}^{n}(w_j a_j) \Big/ \sum_{k=1}^{n} a_k = \sum_{j=1}^{n} w_j f_j$$

Table 1: Snow depth and density for various terrains, Fosheim Peninsula, May 1994

Terrain	Snow depth (mm)			Snow density (kg/m^3)			Snow water equivalent (mm)
	#transects	mean	s.d.	# samples	mean	s.d.	
Rolling Upland	11	163	34	19	280	60	46
Plateau	3	173	16	5	297	56	51
Wetland and lake	3	154	47	6	315	29	49
Flat valley floor	2	141	29	5	304	61	43
Valley	6	201	36	11	276	58	56
Gully	7	497	129	15	307	62	153
Thermokarst	1	298	-	3	343	55	102
Slopes:							
North	2	311	88	6	296	42	92
Northwest	1	295	-	2	321	70	95
East	2	153	36	4	250	24	38
Southeast	1	166	-	3	243	36	40
South	3	184	65	5	313	37	58
West	4	162	14	4	284	83	46

with a_j being the area, w_j being the water equivalent of terrain j, and

$$f_j = a_j \Big/ \sum_{k=1}^{n} a_k$$

being the fractional area within the pixel occupied by terrain j.

For the Fosheim Peninsula, two pixel areas were selected, one east of the Hot Weather Creek and the other west of it (Figure 2). Although the accuracy of a SSM/I pixel geolocation is ±7 km (Colton, 1995, personal communication), for the purposes of this study the latitude and longiitude pixel references were assumed to be accurate. Calculations of W_p made use of the pooled mean depths and mean densities given in Table 1, except for rolling upland and plateau where values for the sectors east or west of Hot Weather Creek were substituted. Table 2 provides the w_j and f_j values and the computed mean snow water equivalents for the two pixel areas. The mean snow water equivalent is 53 mm for the eastern pixel and 50 mm for the western one.

Subpixel variability

Snow distribution is often uneven within a pixel. The subpixel variation of snow water equivalent is examined using the two sample pixels selected. The eastern area is dominated by rolling terrain with wetlands and lakes occupying the depressions and shallow valleys (Figure 2). In contrast, the western pixel covers a highly dissected area which includes many gullies and valleys, slopes of different orientations, wetlands, rolling areas and disseted plateaus.

To quantify subpixel variability, the snow condition is treated as a variate grouped into various classes, each represented by the water equivalent of a terrain type. Variability is expressed as the standard deviation (s) of the grouped variate (Kenney and Keeping 1954):

$$s = \left[\sum_{j=1}^{n} f_j (w_j - W_p)^2 \right]^{1/2}$$

where W_p is the mean snow water equivalent for the pixel, w_j and f_j are the water equivalent and fractional snow coverage of terrain j. Table 2 provides the values for calculating the subpixel variabilty and the resulting standard deviations are 13.4 mm and 30.7 mm for the eastern and the western pixels.

The results show that the eastern pixel with even topography and more uniform snow cover has less

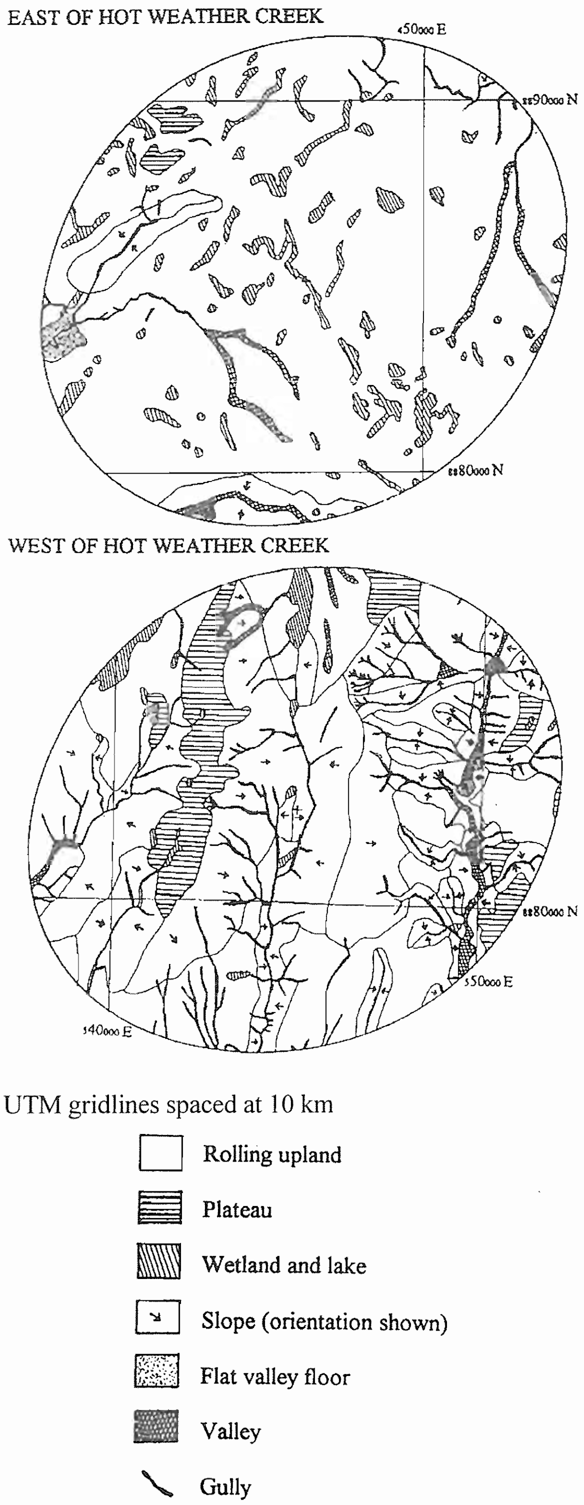

Figure 2: Distribution of terrain types in two sample pixel areas, east and west of Hot Weather Creek.

subpixel variation than the western pixel which covers more rugged areas with a greater variety of snow conditions. Information on variability, though important on a local scale, cannot be obtained from satellite imagery because of its coarse resolution.

SNOW COVER PATTERN FROM SATELLITE

Figure 3 depicts the spatial pattern of 85 GHz horizontal polarization brightness temperatures for one SSM/I orbit over the study area on May 8, 1994. The locations of each of the 85 GHz pixels are displayed (+), giving an indication of the coarse spatial resolution of the SSM/I data. The pixel used in the analysis of snow conditions east of Hot Weather Creek is from this orbit and is represented by the ellipse.

Despite the relatively coarse resolution of the SSM/I data, spatial variability in the 85 GHz brightness temperatures is evident across the Fosheim Peninsula, which may be related to regional variations in snow cover. The brightness temperatures decrease eastwards from Eureka across the peninsula, suggesting that the amount of snow on the ground is increasing in the same direction. This brightness temperature pattern is typical of all the SSM/I orbits acquired during the May 1994 snow survey period. The two pixels selected for analysis both fall within the 205-210°K range of brightness temperatures, indicating that the amount of snow on the ground is relatively similar for the two locations. The areally weighted snow water equivalent values for these pixels listed in Table 2 confirm that the difference between the two pixels is small (less than 4 mm).

Although it is too preliminary to establish a direct relationship between the SSM/I 85 GHz brightness temperatures and the observations of snow water equivalent based on one survey, the results are promising. Further snow surveys are planned for Fosheim Peninsula in 1995 and 1996, which will hopefully lead to greater understanding of the relationship between SSM/I brightness temperatures and regional snow conditions and the development of a reliable SSM/I snow water equivalent algorithm for the region.

CONCLUSIONS

This study introduces a new method of snow survey in which extensive traverses are employed to obtain regionally integrated snow information. Such information is becoming increasingly important for global scale modelling and to enable the development of algorithms for satellite surveillance of regional snow cover.

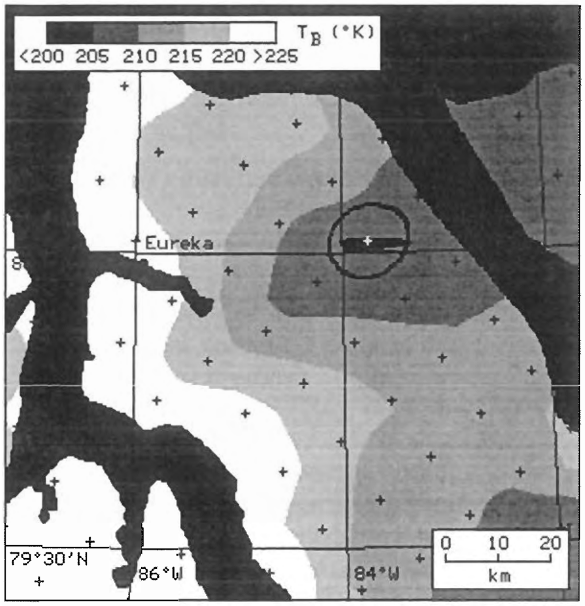

Figure 3: SSM/I 85 GHz microwave brightness temperatures (horizontal polarization) for Fosheim Peninsula and adjacent areas, May 8, 1994. Pixel locations are indicated by the "+" symbols. The areal coverage of the pixel that was selected for analysis of snow conditions east of Hot Weather Creek is represented by the ellipse.

For the High Arctic, terrain is the major factor controlling local scale snow distribution, but regional scale variation also contributes to snow cover variability. Satellite data from the SSM/I microwave radiometer offer a promising way to map regional variations in Arctic snow cover. Each SSM/I 85 GHz pixel covers a 150 km^2 area on the ground. Within the area covered by a pixel, variability of snow cover may be considerable. A single station observation in a pixel cannot represent this variability, nor can the standard ten-point snow course even if designed to sample some of the local effects. The transect approach used in this study incorporates multiple sampling at regular intervals to provide more representative samples of the regional snow conditions and avoids being biased by local effects.

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Table 2: Fractional area with different terrain types covering two sample pixels

Terrain	Fractional area of pixel	
	West of HWC	East of HWC
Rolling Upland	0.274	0.847
Plateau	0.091	0.008
Wetland and lake	0.020	0.029
Flat valley floor	0	0.005
Valley	0.023	0.019
Gully	0.074	0.014
Thermokarst	0	0
Slopes:		
North	0.028	0.008
Northwest	0	0.009
East	0.298	0
Southeast	0	0.015
South	0.028	0.014
West	0.163	0
Snow water equivalent		
Mean (mm)	49.5	53.1
Variability (mm)	30.7	13.4

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