STRATIGIES FOR MEASURING SNOW WATER EQUIVALENT FOR HYDROLOGICAL APPLICATIONS: PART 2, SPATIAL DISTRIBUTION AT THE WATERSHED SCALE

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ABSTRACT

One of the challenges for hydrologists is to make predictions of the runoff response of Arctic watersheds. This is especially true for snowmelt when data is sparse and of poor quality, solid precipitation is redistributed by wind events and sublimation can deplete the snowpack. At the small watershed scale we can saturate the catchment with measurements to get a good approximation of the snowpack. However, for larger basins this is not logistically possible. In this paper we talk about our present snow water equivalent (SWE) measurement strategy for a group of nested watersheds on the North Slope of Alaska in which we try to capture the spatial variability. We present some concentrated field measurement techniques to evaluate our normal sampling protocol. These results show that our techniques work for capturing SWE variability from scales ranging from 100 m to 10,000 m and possibly more. We cannot capture SWE differences for scales less than a few meters such as an incised stream. We need to couple our field measurement program with a blowing snow model and compare results for large watersheds (>10,000 km^2).

KEYWORDS

Snow distribution, watershed scale, Arctic, Alaska, snow depth, SWE

1. INTRODUCTION

Snow water equivalent (SWE) on the ground at a point cannot be accurately estimated by the amounts of solid precipitation that falls because of large biases in gauged precipitation (Goodison *et al.*1998; Yang *et al.* 2000) and the horizontal wind-blown fluxes and vertical sublimation. Regardless, hydrologists interested in the snowmelt runoff response of a watershed need to know the spatial SWE distribution just prior to melt. Accepting that there is natural spatial variability of solid precipitation amounts due to topographic factors at scales of 10s to 100s of km, redistribution of the snowpack by wind events during or following deposition at various scales surrounding the 1 km distance ensure that the Arctic snowpack at the watershed scale will be very heterogeneous by winter's end. Complicating this further, during the winter months prior to ablation, sublimation is ongoing and primarily controlled by the amount of energy available.

Hydrologically, we are challenged to capture the heterogeneous distribution of this snowpack for use in, for example, hydrologic models for water balance determinations (Bowling *et al.* 2003; Kane and Yang 2004; Lilly *et al.* 1998) and prediction of snowmelt runoff (Zhang *et al*. 2000). We presently have a routine for taking field measurements of both snow depth and snow water equivalent (SWE) at the watershed scale from 2 to over 8,000 km^2 (Figure 1). We address in this paper the question, does this technique adequately capture the snow distribution over these watersheds that range in drainage area by circa five orders of magnitude? There are several logistical obstacles that limit the approaches we can take to quantify snow depth and SWE: first, most of the area is very remote and only accessible by helicopter, second, some of the area is quite mountainous and not even accessible by helicopter and finally, as usual man-power and financial resources are limited.

2. SETTING

The North Slope of Alaska is an extensive area that transitions from the continental divide in the Brooks Range to the Arctic Ocean. There are three distinct topographic regions on the North Slope: mountainous, foothills and coastal plain (Kane et al., 2000). The entire region is underlain with permafrost that reaches a maximum thickness of greater than 600 m. Except for a few isolated riparian areas in the foothills, the area is treeless. Shrubs (0.4 to 1.0 m) are common throughout the watersheds with higher density in foothills; shrubs are increasing in density. The active layer is typically about 50 cm (varies considerable due to vegetation, soils, aspect, slope, etc.) with extensive surficial organic soils overlying mineral soils. Lakes can be found throughout the region, but are found in much greater numbers on the coastal plain. All of the streams are predominantly north draining with some streams having extensive aufeis. Winters start in mid-September with breakup occurring from early May to early June. It can snow on any day of the year with usually three or four snow events during the summer.

3. METHODOLOGY

Through intensive field measurement campaigns we attempted to quantify the snow depth and SWE distribution (Figure 2) at the watershed scale at winter's end. Basically we take 50 snow depth measurements in an L-shaped pattern, along with five SWE measurements at numerous sites in a watershed. The distribution with elevation of snow survey sites in the Kuparuk River basin is shown in Figure 3. In general, the lone criterion for site selection was that the measurement area (generally 25 to 50 m) is representative of a much larger surrounding area (same slope, aspect, vegetation, etc.). This technique however fails to capture snow variability that may exist at smaller scales such as a small-incised drainage.

One feature of our field sampling effort is that the density of the stations decreases significantly as the watershed size increases. The densities are 0.22, 7.1, 23.6 and 106 km^2/site for Imnavait Creek (2.2 km^2), Upper Kuparuk River (142 km^2), Putuligayuk River (471 km^2) and Kuparuk River (8,140 km^2) respectively. The measurements in Imnavait Creek differ from the other watersheds; originally when this was the only watershed being studied, we did a 1000 m transect across the catchment from ridge to ridge, with five SWE measurements every 100 m. It is not realistic to do such transects on larger watersheds.

The rationale for taking five SWE measurements where we get the density and 50 snow depth measurements is that the depth (Figure 4) varies much more than the density (Figure 5). What this means is that in a given amount of time, snow depth measurements will yield more information to quantify the snowpack than will density measurements that yield the SWE. Snowpack densities can vary from 150 to 350 kg/m^3, but typically there are in the range of 200 to 300 kg/m^3 (Figure 5). Snow depth can vary from snow free to over 2 m in localized areas of drifting. From the five density measurements we get an average density that we use with the average of the 50 depths to get an average SWE.

We have compared snow density estimates obtained from the Adirondack tube that we use versus snow pits and Mt. Rose snow sampler used by federal agencies; the results are quite comparable. However, there is a certain amount of error introduced in the depth measurements. In the area of study, surface organic soils prevail. When inserting the probe into the snowpack, it is difficult to ascertain the interface between the bottom of the snowpack where large crystals of depth hoar are found and the surface of the organic soils (Berezovskaya and Kane, 2007). By taking depth measurements in the usual way with a probe at a 1 m interval, we then excavated a trench along the transect where measurements were made and the true depth could be observed. Results show that we over estimate the snow depth on an average of 8 cm (or in a typical year ~20%). It should be noted that the error associated with snow depth measurement with the probe is greater than the tube. Also a certain human element is linked with the depth measurements in that no two people will do it with the same vigor.

Two other efforts to evaluate how well we are capturing SWE and snow depth variability are *"starburst sampling"*, i.e. detailed sampling in a starburst pattern (Figure 6), and *"scaling sampling",* i.e. snow depth sampling along transects of varying lengths from 1 m to 100,000 m (Figure 7). With the starburst sampling, we can get a very good idea of the snow depth statistics in a circle with a diameter of 100 m. Then subsets of the larger population can be compared with various less intense sampling schemes. For example, from this pattern, we can get eight possible L-shaped sampling schemes with 25 snow depths on each leg or eight L-shaped sampling schemes with 50 depth measurements on each leg.

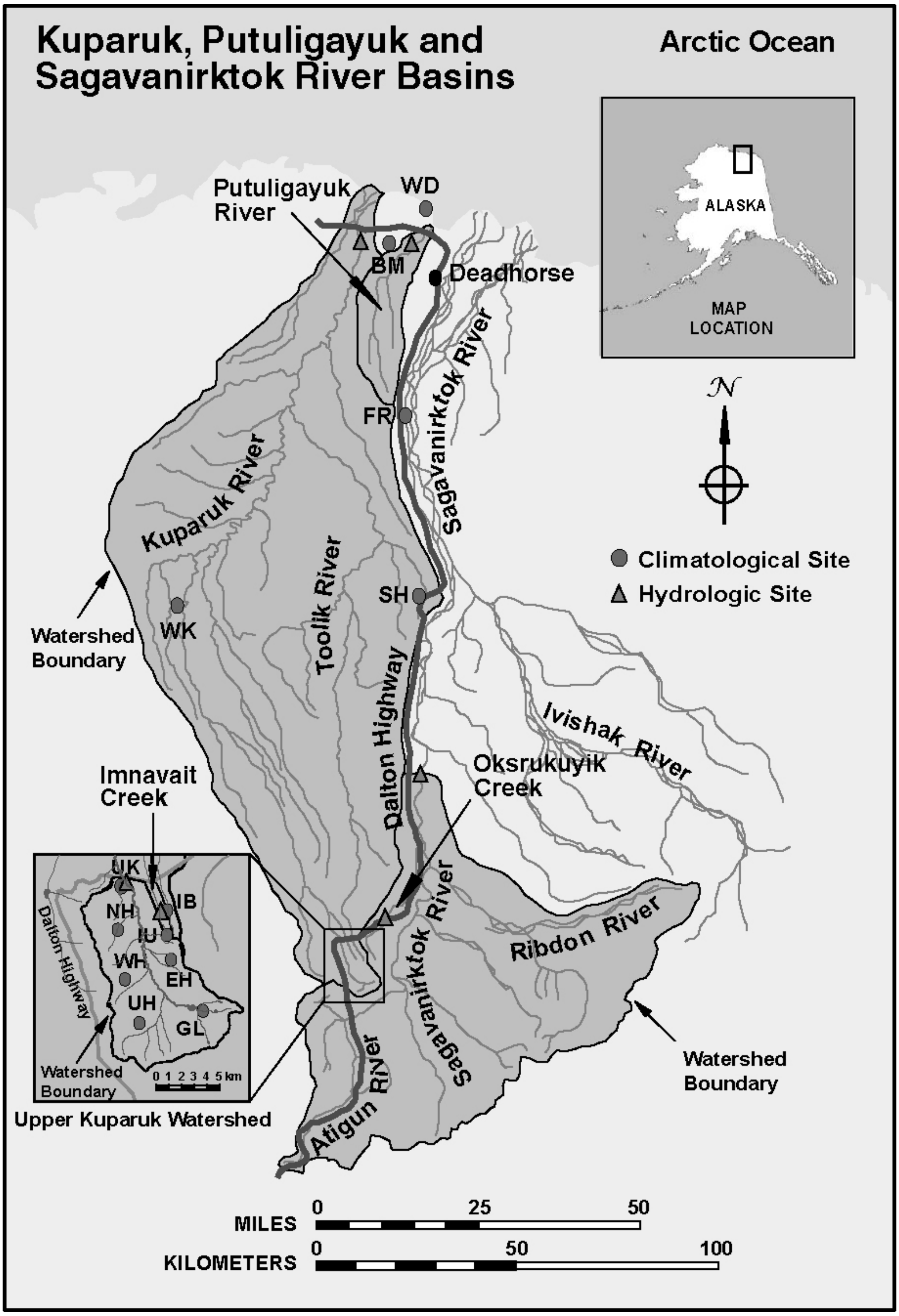

Figure 1. Location map of Kuparuk, Putuligayuk, Upper Kuparuk (insert) and Imnavait (insert) watersheds on the North Slope of Alaska.

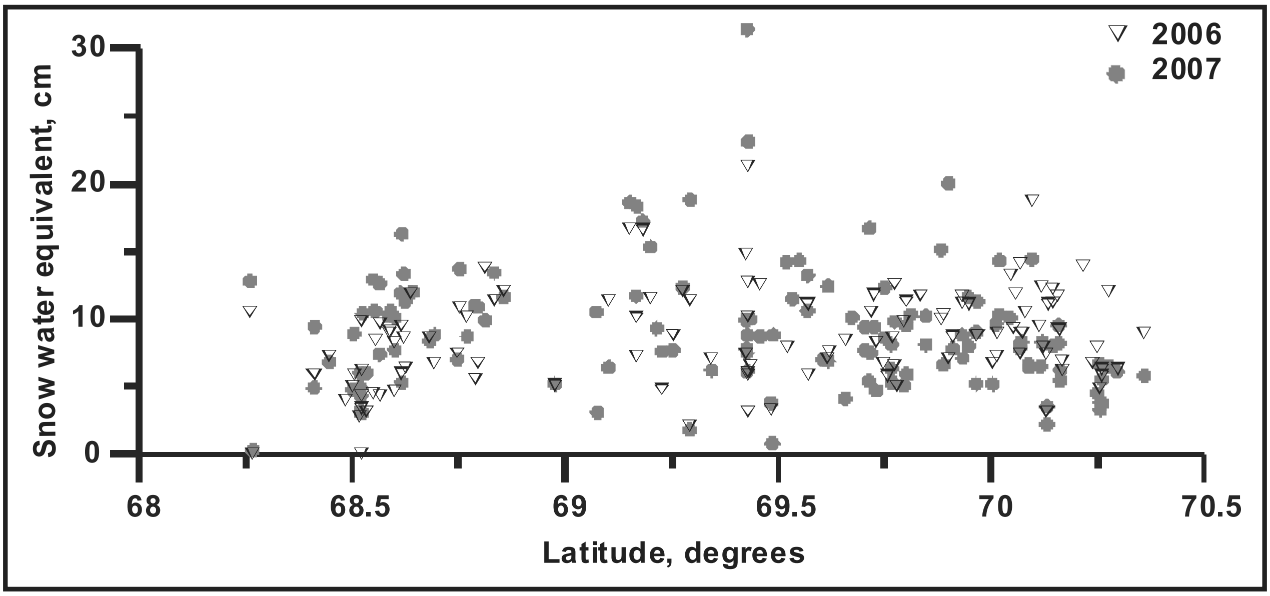

Figure 2. Variation of SWE (cm) with latitude over two winters in the central Arctic of Alaska.

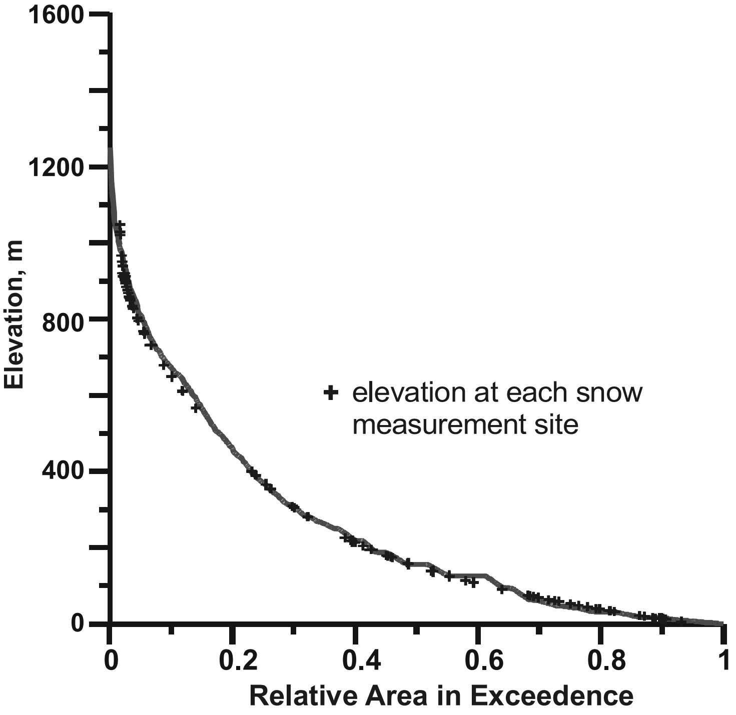

Figure 3. Each symbol on the hypsometric curve for the Kuparuk River basin represents a snow survey site.

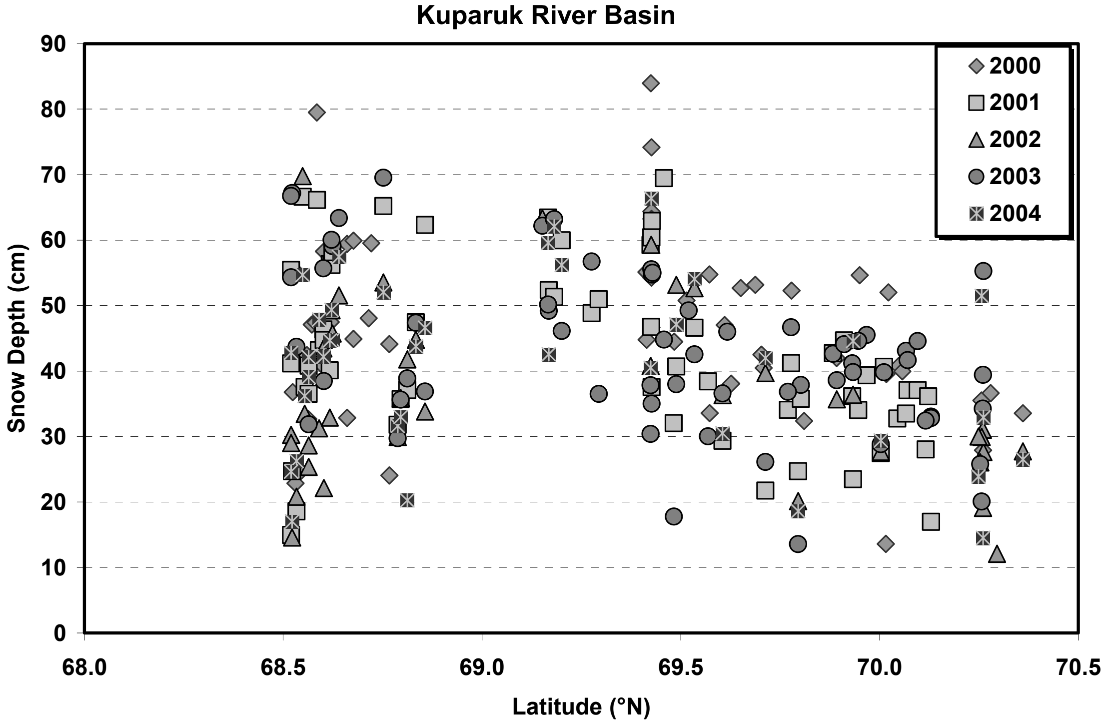

Figure 4. Average snow depth at a site (n = 50) as a function of latitude; individual snow depths can vary by greater than an order of magnitude.

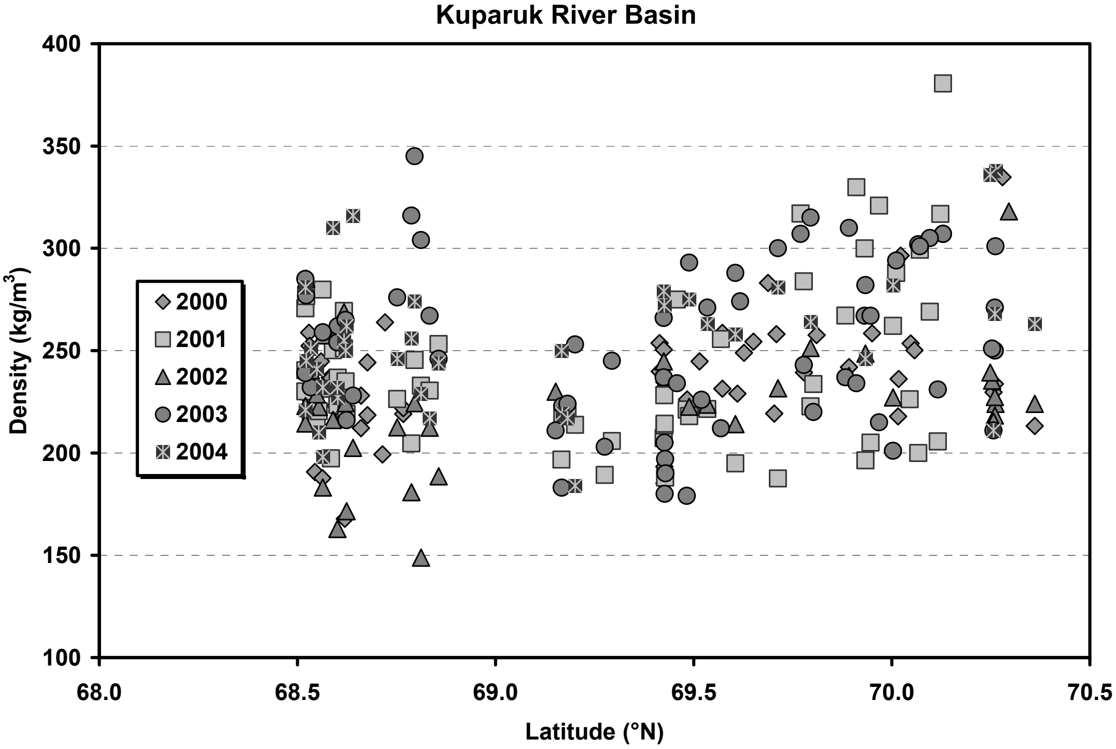

Figure 5. Average snow density (n = 5) as a function of latitude; most densities fall in the range of 250 □50 kg/m^3.

The rationale behind doing the transect studies is to see how much variability there is along transects of varying lengths. Are we amiss at believing that our L-shaped surveys (25 m by 25 m) are representative of much larger areas? Each transect length was divided into 100 equal lengths and the snow depth was then measured at that spacing along a straight line. The only exception is the 100 km long transect (100,000 m) where measurements were made along ten 10 km legs that were parallel. Otherwise the people collecting the data on snow machines would have ended up 100 km from the starting point.

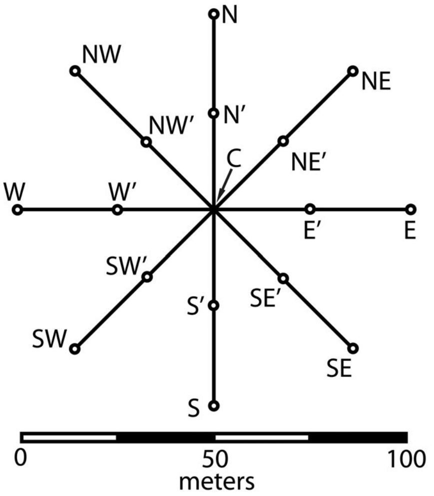

Figure 6. Starburst sampling diagram for snow depth measurements (n = 404) at an intensive site. Various sampling configurations (n = 50 or 100) can be compared statistically with those of all points.

4. RESULTS

4.1 Starburst sampling

The starburst pattern is used to evaluate how well our L-shaped pattern of snow depth measurement at each site captures the statistical average. Snow depths along four transects (N/S, E/W, NE/SW and SE/NW) 100 m long are measured at 1 m intervals (n = 404); in Table 2, three of the possible measurement possibilities are compared (L-shaped 50 measurements, L-shaped 100 measurements and a straight line 100 measurements). The mean of the entire snow depth population is 49.8 cm. The subsets can be identified using Figure 4; for example, the first one reads N’ to C (center) to E’. For L-shaped subset (n = 50), the mean varied from 44.1 to 50.3. This can be compared to L-shaped pattern (n = 100) where the mean varies from 48 to 51.9 cm. For the four straight transects (n = 100), the mean varied from 48.8 to 51.1. The standard deviations varied from a low of 6.3 to 10.4 cm. Generally, the 50 measurements scheme gives a fairly representative estimate of the areal mean, capturing 89 to 101% of our best estimate (404 points). The mean of 100 L-shaped measurements varies from 96 to 104 % of entire starburst mean and captures 98 to 101 % of areal snow depth for the straight line (n = 100). Five other starburst-sampling efforts have been carried out with similar results.

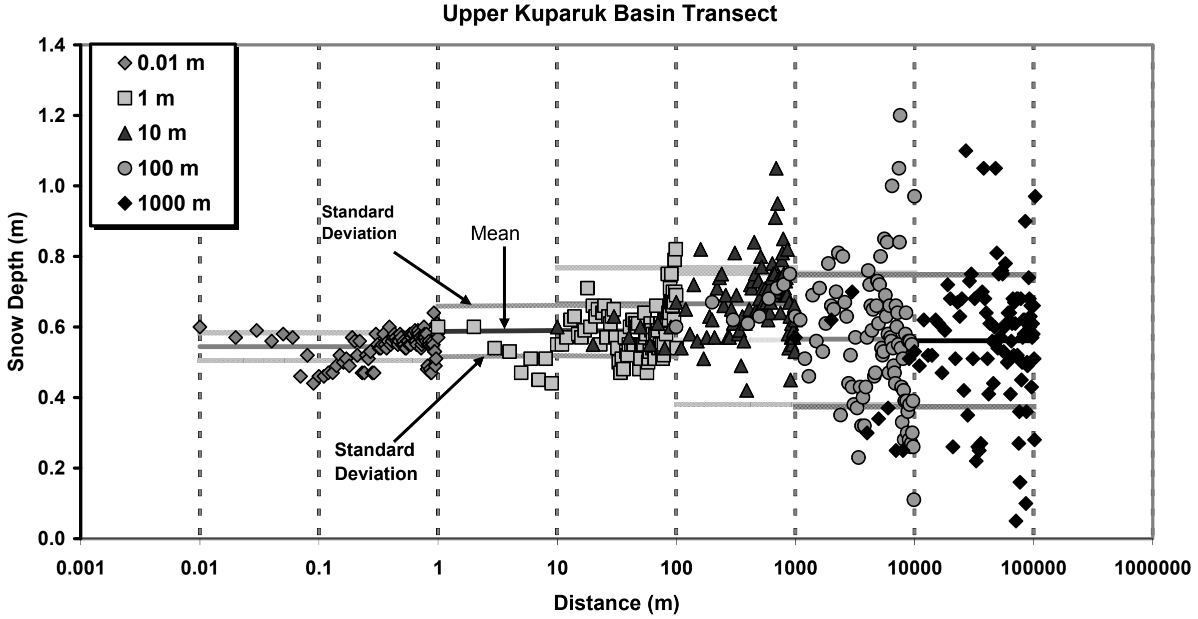

Figure 7. Variation of snow depths (n = 100) along transects of different length.

4.2 Scaling sampling

Scaling sampling allows us to analyze snow depth mean and variance from 100 points over different areal extents (from 1 m to 100 km) and different sampling intervals (from 1 cm to 1 km) thus bridging the gap between our sampling sites to the larger watershed scale. The transect data (Figure 5) shows that although the average depth (n = 100) is quite similar (Table 1) in April 2001 in the Upper Kuparuk drainage, the variability (standard deviation and range) increases with areal data extent. The fact that the 1 m transect mean agrees with the mean of the longer transects is probably a lucky coincidence in that the observer picked an average point. The average depth ranged from 0.54 m (1 m transect) to 0.67 m (10, 000 m). The standard deviation increased from 0.04 (1 m transect) to 0.19 cm (100,000 m transect), as would be expected. The data in the last column represents data collected in Imnavait Creek where 706 snow depth measurements were made along a 1000 km transect every 1.5 m.

4.3 Watershed scale

Our ultimate goal is to quantify the spatial distribution of the SWE at all watershed scales. Some of our past results for predicting the snowmelt runoff response and water balance of Arctic catchments have been less than stellar, especially for large watersheds like the Kuparuk River basin. Water balance determinations for Imnavait Creek, Upper Kuparuk River and the Putuligayuk River have been reasonable and believable for a variety of reasons from the small size of Imnavait catchment to the low-gradient Putuligayuk watershed. Higher than expected runoff ratios for the Kuparuk River (Lilly *et al.* 1998) for some years could only be due to overestimating the distributed SWE or underestimating the runoff.

Since we made those determinations of the runoff ratio, we have increased the density of our distributed SWE measurements for the whole of the Kuparuk River and adjacent watersheds (Table 3). Still, the complexity of SWE pattern requires an extremely large number of sampling points to represent spatial variability unless we have some process understanding that can define pattern features. Our plan is to apply snow transport model for the entire Kuparuk River using annual snow survey data for model calibration (Liston and Elder, 2006). Model performance can be successful with reliable atmospheric forcing, particularly wind and snowfall data, as well as high-resolution terrain and vegetation coverage.

Table 1. Statistics for the measured snow depth (n = 100) along transects of various lengths from 1 m to 100,000 m. The last column with the asterisk represents 706 depth measurements made over 1000 m.

Measurement Spacing (m)	0.01	1.0	10	100	1000	1.5*
Average (m)	0.54	0.59	0.67	0.57	0.56	0.56
Standard Deviation (m)	0.04	0.07	0.10	0.19	0.19	0.10
Minimum (m)	0.44	0.44	0.42	0.11	0.05	0.27
Maximum (m)	0.64	0.82	1.05	1.20	1.10	0.97

5. CONCLUSIONS

Snow depth and SWE are depleted in areas exposed to the wind and enhanced in leeward, low-lying and shrubby Arctic areas discussed here. There is a slight trend of increasing density with increasing latitude, in some years this is offset by decreasing depth with increasing latitude so the variation in SWE is unchanged. From the data presented here, it appears that our measurement scheme of 50 measurements in an L-shaped pattern gives a fairly good representative estimate of the average over 100 m and in some cases for distances of 10s of kms. It is also clear that for small incised streams (~ 2 to 3 m) and abrupt topographic changes (lake edge) of the same scale that we will not capture that variability. This in unfortunate since the SWE in these environments can exceed that in the open tundra by a substantial amount (a factor of 8 in one case measured in spring 2007). This is important hydrologically because this water is situated either in or closely adjacent to the drainage network.

To accurately predict the distribution of snow on the ground in this treeless, windy environment at winter's end, we need good data on winter solid precipitation (presently lacking), good digital elevation data, and a robust blowing snow model. We presently have good digital elevation data for some areas, but not most. Several blowing snow models exist (Pomeroy *et al.* 1997; Liston and Sturm 2002), but they require reliable forcing and assimilation data for successful performance. We could also use better vegetation data sets as shrubs are very efficient at trapping snow. With a combination of good winter precipitation data, digital elevation data and snow transport model, we will be able to use the data collected in the field and presented here for quantifying snow water equivalent distribution in the Arctic. We still have some challenges ahead of us, but it is crucial that we achieve this goal as the snow accumulation and ablation process is an important hydrologic event in the Arctic each year.

Table 2. A comparison of mean and standard deviation of various transects (n = 50 or 100) to the entire starburst data set (n = 404).

Subset	# of Points	Mean (cm)	Std. Dev. (cm)
Entire Starburst	404	49.8	8.1
L-Shaped Pattern, 25 m by 25 m			
N'2C2E'	50	50.3	10.4
E'2C2S'	50	47.5	8.1
S'2C2W'	50	44.1	6.3
W'2C2N'	50	47.2	8.0
L-Shaped Pattern, 50 m by 50 m			
N2C2E	101	51.9	9.0
E2C2S	101	51.9	9.0
S2C2W	101	48.0	8.0
W2C2N	101	49.9	7.9
Straight Transect, 100 m			
N2C2S	101	48.8	8.5
NE2C2SW	101	51.1	8.9
E2C2W	101	50.1	7.3
SE2C2NW	101	49.0	7.8

Table 3. Watershed average snow water equivalent (cm) on the North Slope of Alaska

	2006	2007	2006	2007
		Kuparuk River	Sagavanirktok River	
Mountains	6.7 (n=7)	6.3 (n=7)	7.3 (n=14)	6.7 (n=17)
Foothills	8.9 (n=39)	11.5 (n=41)	9.6 (n=6)	8.3 (n=13)
Coastal plain	9.5 (n=12)	9.9 (n=22)	9.4 (n=7)	7.5 (n=3)
Basin average	8.4 (n=58)	9.2 (n=70)	8.8 (n=27)	7.5 (n=33)

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