

Spatial distribution of near surface soil moisture and its relationship to microtopography in the Alaskan Arctic coastal plain

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Abstract The Arctic coastal plain of Alaska is characterized by marked heterogeneity in microtopography and above ground vegetation productivity at a variety of scales. This heterogeneity may be expected to lead to large variations in near surface soil moisture and have a substantial impact on measured and modeled fluxes of carbon and water. In this study, we hypothesized that microtopography was the primary control over the spatial patterns of near surface soil moisture. Near surface soil moisture measurements were collected in the summers of 2000, 2001, 2002 and 2003 in the fetch of an eddy flux tower (0.5 km²). Results confirmed the expected relationship between intra- and inter-seasonal variations in near surface soil moisture and variations in precipitation. However, over two time periods, near surface soil moisture increased without corresponding measured precipitation inputs and this was attributed to fog and dew, which are difficult to measure, and/or the melting of the active layer. Spatial variations in near surface soil moisture are largely controlled by microtopography in areas characterized by high centered polygons and troughs. In areas without large variations in microtopography, macrotopography, in the form of drained thaw lakes, has a substantial control over near surface soil moisture.

Keywords Arctic; microtopography; permafrost; permafrost features; surface soil moisture

Introduction

Warming in northern, high latitude ecosystems is expected to affect regional climate patterns, the surface energy balance, the depth of the active layer (the near surface layer of soil or earth materials above the permafrost that experiences seasonal freezing and thawing) and hydrologic processes (Kane *et al.* 1991, 1992; Gates *et al.* 1992; Hinzman and Kane 1992a; Waelbroek *et al.* 1997). Global circulation models predict mean global temperature to increase 1.3–2.3°C with a doubling of atmospheric CO₂, but the most significant temperature increases are expected to occur at high latitudes (Manabe and Stouffer 1993; Meehl *et al.* 1993; Kattenberg *et al.* 1996). Evidence from thermal profiles of permafrost and meteorological records indicates that an increase in temperature of 2–4°C over the last few decades has already occurred throughout northern Alaska, western Canada and the Siberian Arctic (Chapman and Walsh 1993; Oechel *et al.* 1993; Overpeck *et al.* 1997; Serreze *et al.* 2000). These changes could potentially alter the surface energy and carbon balance in Arctic ecosystems (Chapin *et al.* 2000).

In order to improve scientific understanding of the drivers and processes influencing change in Arctic tundra landscapes, the National Science Foundation (NSF) Arctic System

Science (ARCSS) Land Atmosphere Ice Interactions (LAI) research program was initiated. The primary research objectives of the LAI project, Arctic Transitions in the Land Atmosphere System (ATLAS), were 1) to determine the geographical patterns of and controls over the atmosphere land surface exchanges of mass and energy in order to 2) quantify patterns and processes and to develop reasonable scenarios of future change in the Arctic system. The research in this study was conducted as part of the larger ATLAS project and was intended to improve understanding of local scale ($<1\text{ km}^2$) variability in near surface soil moisture, a significant control over carbon, water and energy exchange. Understanding the controls over the spatial distribution of near surface soil moisture would facilitate modeling carbon and energy fluxes by allowing for a more realistic representation of this variable than a single mean value (Wetzel and Chang 1987; Famiglietti and Wood 1994; Bartlett *et al.* 2002).

Soil moisture is a key variable affecting the surface energy balance and carbon cycle in Arctic ecosystems (Chapin *et al.* 2000; Clein *et al.* 2000; McGuire *et al.* 2000). Variations in soil moisture influence the partitioning of the incoming solar radiation into latent, sensible and ground heat flux (Hinzman and Kane 1992b; McFadden *et al.* 1998). Soil moisture also influences decomposition and photosynthesis rates, which may alter the carbon sink or source nature of Arctic ecosystems (Oberbauer *et al.* 1991; Oechel *et al.* 1993; Vourlitis and Oechel 1999; McGuire *et al.* 2000). In the Alaskan Arctic coastal plain where non-vascular vegetation (mosses and lichens) is abundant, the soil moisture at or near the surface is important because mosses lack roots or their functional equivalents to extract subsurface water (Oechel and Sveinbjornsson 1978). Non-vascular vegetation contributes significantly to production, biomass and cover in these ecosystems (Webber 1974, 1978; Oechel and Sveinbjornsson 1978; Rastorfer 1978) while representing up to 75% of the evaporation from the surface (Miller *et al.* 1976). Because carbon dioxide assimilation and evaporation rates from non-vascular vegetation are strongly controlled by moisture content (Williams and Flanagan 1996; Oechel and Sveinbjornsson 1978), near surface soil moisture can have a large impact on the carbon and energy exchange from Arctic coastal plain ecosystems.

One of the major features in the Alaskan Arctic coastal plain is the presence of permafrost, or perennially frozen ground. Permafrost forms an impervious layer that limits the vertical redistribution of soil water into a deeper soil layer. This causes a perched water table to develop, which in combination with seasonal variations in the depth of active layer, precipitation, water inputs from melting ice, evapotranspiration rates and the lateral redistribution of water, affects temporal variations in soil moisture (Hinkel *et al.* 1996, 2001). Additionally, permafrost has a pronounced effect on the spatial variation in soil moisture due to the patterned ground that develops in response to the freezing and cracking of soil and ice into the formation of regularly spaced ice wedge polygons (Tieszen 1978). In general, polygons can be classified into two types, low and high centered (Hussey and Michelson 1966). Low-centered polygons are features in which the polygon center is enclosed by peripheral ridges, while high-centered polygons are features where the polygon center is a mound outlined by troughs (Hussey and Michelson 1966). The resulting microrelief from polygon formation leads to variations in soil moisture and vegetation that can be of considerable ecological significance (Wiggins 1951).

Small area (for this study, areas less than 1 km^2) heterogeneity, in particular soil moisture heterogeneity, could lead to large uncertainty in modeled estimates of carbon and energy fluxes due to the non-linearity of the processes involved (Wood 1994, 1997; Sellers *et al.* 1997; Ostendorf *et al.* 2001). Heterogeneity in soil moisture often occurs at spatial scales below the grid size of most hydrologic or hydro-ecophysiological models. A number of different approaches have been developed for mid-latitude ecosystems to represent sub-grid scale heterogeneity, including stratification of the landscape into units that represent varying

degrees of wetness and statistical dynamical approaches (e.g. Wetzel and Chang 1987; Beven and Kirkby 1979; Famiglietti and Wood 1994; Bell *et al.* 1990). However, little or no research has been directed at understanding and representing small-area soil moisture heterogeneity in Arctic landscapes (Chapin *et al.* 2000).

Research objectives

A time series of near surface soil moisture data has been collected by LAII ATLAS scientists along seven, 400 m long, permanent transects within the fetch of an eddy flux tower. The sampling scheme was developed for multiple objectives as part of the larger LAII ATLAS project and was based on an assumption that the sampled data would be representative of the near surface soil moisture across the entire fetch of the eddy flux tower, an area approximately 0.5 km² (Hope *et al.* 1995). Therefore, the initial objective of this study was to determine if the soil moisture distribution measured along the permanent transects was significantly different from the distribution of soil moisture measured across the entire study area. A second goal was to determine the spatial and temporal variability in near surface soil moisture over a four year period and to determine the relative control of precipitation and microtopography on this variability. While variations in evapotranspiration may affect temporal and spatial patterns in near surface soil moisture, we hypothesized that precipitation was the major influence on the temporal variability in near surface soil moisture and microtopography was the primary control over the spatial patterns of near surface soil moisture.

Study area

The study site is located on the Arctic coastal plain near Barrow, Alaska (71°19'N, 156°37'W) and covers approximately 0.5 km² (Fig. 1). The site is part of a larger LAII ATLAS project and encompasses the fetch of an eddy flux tower. Vegetation in the study area is mesic tundra dominated by the herbaceous sedges *Carex aquatilis* and *Eriophorum scheuchzeri*, the most common vascular vegetation types within the Barrow region (Brown *et al.* 1980). The depth of the underlying layers of moss, lichen and organic matter varies substantially across the study area, from non-existent at the tops of high-centered polygons to approximately 200 mm in depth within the wet, polygon troughs. The two soil types in the study area are *Typic Aquiturbels* and *Typic Molliturbels* (Boekheim *et al.* 1999; Michaelson and Ping 2003). Mean annual temperature is approximately -13°C (Walker *et al.* 1980) and average summer temperature (June–August) is 2.5°C (Brown *et al.* 1968). Mean warm period is 1 June to 31 August, precipitation is approximately 57.7 mm (NCDC 2004). Frequent fog and drizzle occur in the study area (Walker and Acevedo 1987) due to its close proximity to the Arctic Ocean (approximately 0.5 km).

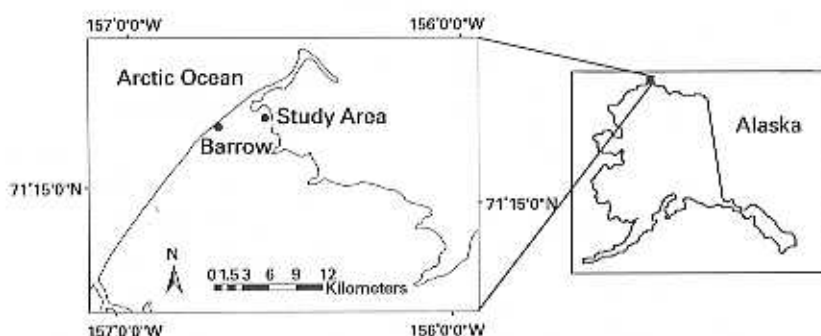


Figure 1 Study area location near Barrow, Alaska

The entire study area is underlain with permafrost that has a seasonal depth of thaw (active layer depth) ranging from 30–90 cm in thickness (Hinkel *et al.* 1996, 2003). The study area contains a variety of the macrotopographic features including portions of three drained thaw lakes of varying ages and a flat upland area that fails to show evidence of thaw lake activity (Hussey and Michelson 1966). This macrotopography leads to differences in relative topographic position within the landscape, because the upland area is approximately 3–5 m higher in elevation than the thaw lakes. Differences in the ages of the thaw lakes, from recent to ancient as mapped by Hussey and Michelson (1966), led to variability in the microtopography within the study area (Hinkel *et al.* 2003). The eastern portion of the study area contains remnants of a recently drained thaw lake which has areas without polygonal features (i.e. featureless) and flat-centered polygons. Flat-centered polygons are indistinct ice-wedge features with little microrelief (less than 0.25 m) that are found in medium and old drained thaw lake basins as described by Hinkel *et al.* (2003). In the southern portion of the study area, there is a shoreline of an ancient thaw lake, which leads to substantial microtopography characterized by high-centered polygons outlined by troughs (Hussey and Michelson 1966). The northern and western sections of the study area include a portion of a recently drained thaw lake and its shoreline which contains a combination of featureless, flat-centered polygons, troughs and other microsite types. In general, the slopes between the drained thaw lakes and the flat-upland area are gentle. There are a few steeper slopes on the edges of high-centered polygons that occur over short distances (i.e. a few meters). Overall, the range in elevation across the study area is 5.5 m over a distance of approximately 800 m.

Data

Soil moisture

Soil moisture data were collected using a Vitel[®] probe (Model: Hydra soil moisture probe, Vitel Inc., VA, USA) which measures the dielectric resistance in the first 7 cm of the soil horizon. The soil moisture probe was calibrated using 175 dielectric resistances covering a range of water content values including 25 samples of water and 25 samples of oven-dried soil (Fig. 2). The remaining 125 samples were collected from a variety of landscape types to be representative of the landscape in the Barrow region. These samples were collected in the top 7 cm of the soil surface incorporating both the organic and mineral horizons. Volumetric

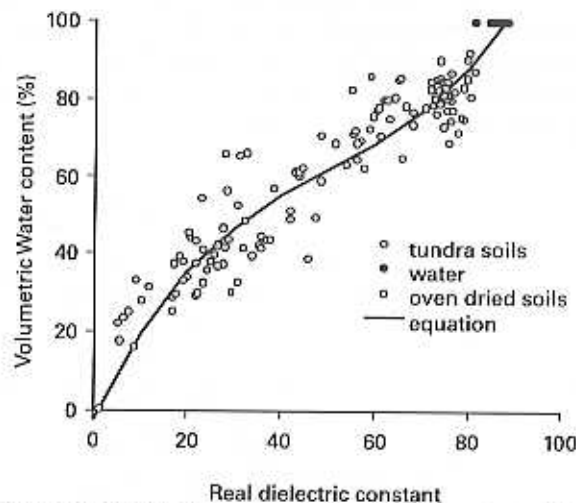


Figure 2 Scatterplot of the relationship between percent volumetric water content and dielectric constant, with a curve representing the non-linear calibration equation developed from all 175 water and soil samples

water contents (VWC) ranged from 16–97% (Fig. 2). Following the approach described by Zamolodchikov *et al.* (2003), a third-order polynomial regression equation was derived to relate VWC to the real dielectric constant and yielded the following expression:

$$\text{VWC} = -2.50 + 2.508E - 0.03634E^2 + 0.0002394E^3 \quad (1)$$

$$r^2 = 0.956, \text{ SE} = 6.8\%, n = 175$$

where VWC is volumetric soil moisture (%) and E is the real dielectric constant.

Near surface soil moisture was measured during the summer growing seasons of 2000, 2001, 2002 and 2003. The LAII ATLAS sampling scheme consisted of measurements along seven permanent transects radiating away from the eddy flux tower in seven directions from 0° to 270° at 45° intervals (i.e. 0°, 45°, 90°, 135°, 180°, 235° and 270°). Along each 400 m transect, 27 flagged points were located 10 m apart from 0–200 m, 20 m apart from 200–300 m and 50 m apart from 300–400 m for a total of 189 measurements locations within the tower fetch.

The flagged points were geo-located using a real-time, differentially corrected global positioning system (GPS) with sub-meter accuracy (Model: Trimble 5700, Trimble Inc., CA, USA). Measurements of soil moisture along the seven transects were made on six dates in 2000 (Julian days 174, 182, 191, 197, 204 and 212), seven dates in 2001 (Julian days 171, 179, 202, 206, 213, 226 and 234), eight dates in 2002 (Julian days 179, 186, 193, 202, 208, 216, 230 and 238) and nine dates in 2003 (Julian days 170, 176, 191, 200, 205, 212, 219, 227 and 233). At each point along the seven transects, three individual measurements were made within a 20 cm² circle and then averaged. In general, the range of the three individual measurements was within the standard error of the calibration equation (Eq. (1)).

A second set of near surface soil moisture data was collected by intensively sampling the entire study area ($n = 751$) over a three day period from 30 July to 1 August 2003. This intensively sampled data set was collected to represent the distribution of near surface soil moisture across the entire study area. Each of the intensively sampled, near surface soil moisture points were geo-located using a differentially corrected GPS with <5 m accuracy. The intensively sampled data collection coincided with measurements at all 189 flagged points along the seven permanent transects on 30 July 2003 (Julian day 211).

Microtopography

At each of the 189 flagged transect points the local microsite type was characterized in June 1998 (Walker, unpublished data). The 189 microsite types were described as follows: troughs (24), low-centered ice wedge polygons (2), depressions (4), high-centered ice wedge polygons (32), flat-centered ice wedge polygons (34), featureless (89) (sites that did not have polygon features) and other (4) frost scar (1), animal den (1) and hummock (2). We combined depressions, low-centered polygons and troughs into a single category labeled "troughs" and did not consider "other" in our comparisons. The resulting four microtopographic categories were: troughs (30), high-centered polygons (32), flat-centered polygons (34) and featureless (89).

Meteorological data

Precipitation data used in this study were obtained from the National Climate Data Center at the W. Wiley Airport, located approximately 5 km from the study site in Barrow. Previous studies have indicated that precipitation data in the Barrow region is significantly under-recorded by the standard National Weather Service non-recording gauge (203.2 mm orifice) (Dingman *et al.* 1980; Benson 1982; Yang *et al.* 1998). Undercatch is due to the large percentage of low intensity precipitation, wetting and evaporation losses, and wind-induced

errors caused by the wind field deformation over the gauge orifice (Dingman *et al.* 1980; Yang *et al.* 1998). Therefore, the warm season precipitation data used in this study were adjusted. Trace events recorded at the weather station were estimated to be 0.10 mm and all measured precipitation events were multiplied by a correction factor of 1.2 for rain based on Yang *et al.* (1998).

Relative humidity and ground heat flux measurements were collected at the eddy flux tower at 30 min intervals. Relative humidity was measured using a moisture sensor (Vaisala, HMP45A) and ground heat flux was measured using two soil heat flux plates (HFT-1, REBS, Seattle, WA, USA). Measurements were sampled every 5 s, quality checked and recorded as 30 min averages.

Results and discussion

Test of the LAII ATLAS sampling design

A time series of near surface soil moisture data were collected along seven permanent transects as part of the LAII ATLAS project. It was assumed that the distribution of near surface soil moisture values measured along these transects was representative of the entire 0.5 km² study area. This assumption was tested by comparing the distribution of near surface soil moisture collected along the seven permanent transects to the intensively sampled data set. The means, standard deviations and histogram shapes of the two distributions were similar (Table 1) (Fig. 3(a, b)). Both samples were positively skewed and had a negative kurtosis indicating light tailed distributions (Table 1). The hypotheses that the variance and means of the distributions between the two data sets were not significantly different were tested. The variances were compared using Levene's statistic for homogeneity of variance and the means were compared using an independent sample *t*-test (Morgan and Griego 1998). Results indicated that both the variance and means of the distributions were not significantly different at the 0.05 level. Therefore, it was assumed that the distribution of near surface soil moisture measured along the seven fixed transects was representative of the distribution of near surface soil moisture across the entire study area.

Near surface soil moisture temporal variability

Both inter- and intra-annual variability in near surface soil moisture values were examined. The annual average near surface soil moisture values were comprised of all measured values over a year. Inter-annual differences in average near surface soil moisture were not large (<10%) and did not follow variations in total warm season precipitation. Despite large variations in warm season precipitation (>46 mm), the annual average near surface soil moisture was relatively stable. This may be expected since feedbacks due to drainage and evapotranspiration modulate near surface soil moisture values.

Table 1 Descriptive statistics for the intensively sampled near surface soil moisture data set and the July 30, 2003 near surface soil moisture data set consisting of all observations at the 189 flagged points along the seven permanent transects

Sample	n	Avg. (%)	Min. (%)	Max. (%)	Std. deviation (%)	Skewness		Kurtosis	
						Statistic	Std. error	Statistic	Std. error
Permanent transects	189	53	14	83	15.8	0.046	0.177	-0.851	0.352
Intensively sampled	751	52	4	87	17.4	0.257	0.089	-0.621	0.178

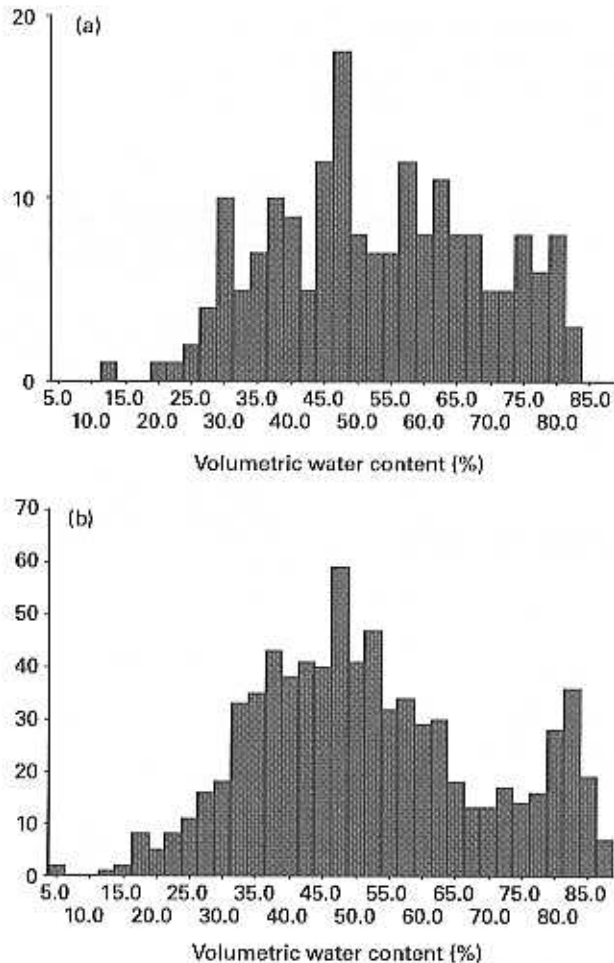


Figure 3 Histograms of the averaged near surface soil moisture measurements made at (a) the 189 points along the seven permanent transects and (b) the 754 points from the intensely sampled data measured throughout the entire study area

Intra-seasonal variations in near surface soil moisture (averages from all 189 flagged points) and daily precipitation are given for all four years (Fig. 4(a–d)). In 2000 the precipitation pattern was the most evenly distributed throughout the warm season (Fig. 4(a)), while 2001 was dry in the early season with an increase in precipitation in the middle to late part of the season (Fig. 4(b)). In 2002, there was some precipitation in the early and late part of the season with very little in the middle (Fig. 4(c)), while 2003 had frequent, light precipitation from Julian day 180 on (Fig. 4(c)). From Fig. 4(a–d), the general trend was that daily variations in precipitation led to variations in the average near surface soil moisture. However, two periods did not follow this general trend: 1) from day 202 to days 208 and 216 during the summer of 2002 (Fig. 4(c)) and 2) from day 170 to 176 in the summer of 2003 (Fig. 4(d)). In these two periods, the average near surface soil moisture increased more than 3% between the start and end dates without substantial precipitation inputs. Due to the large sample size, $n = 567$ (189 points with 3 individual measurements at each point), it is unlikely that the estimation error was substantial enough to explain the apparent increase in near surface soil moisture between these dates. Therefore, other factors may have contributed to the observed increases in near surface soil moisture in the two periods.

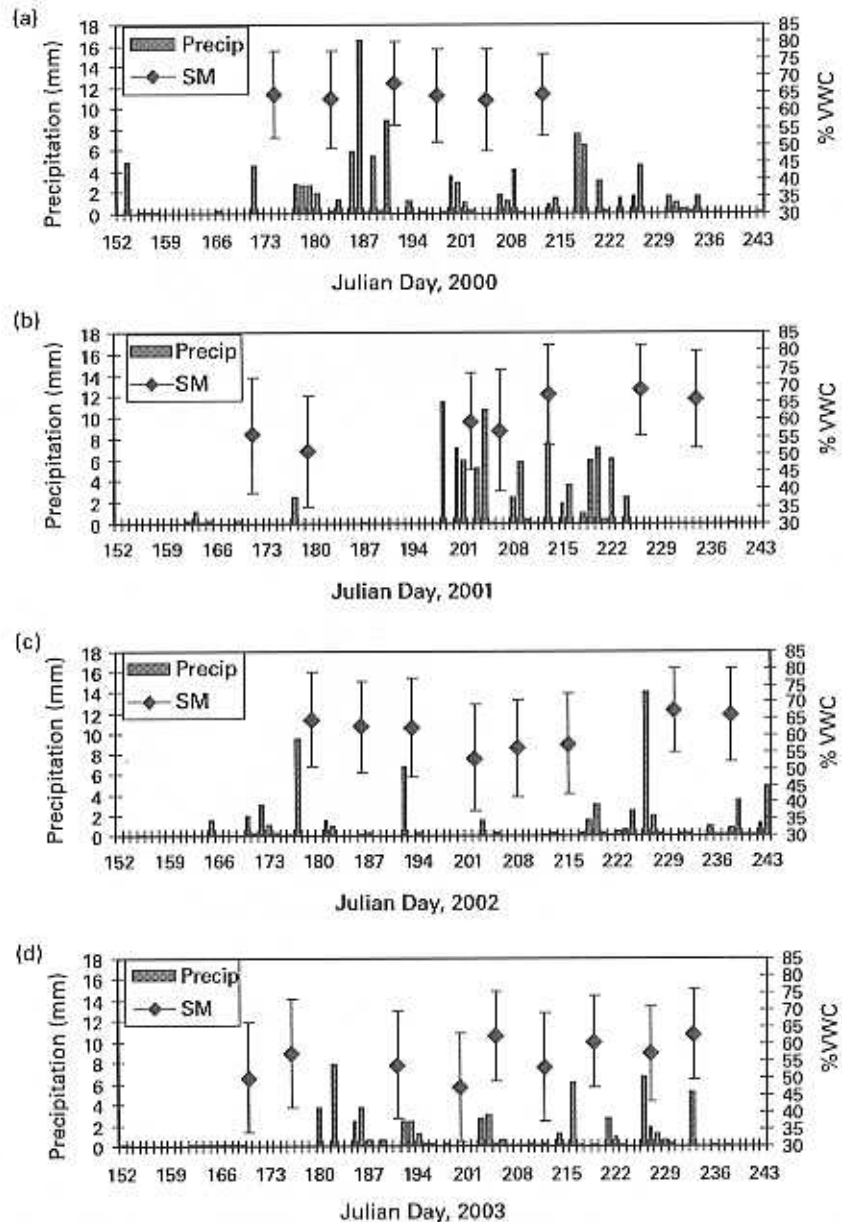


Figure 4 Daily precipitation and average near surface soil moisture for each measurement day plotted over time for a) 2000, b) 2001, c) 2002 and d) 2003. Error bars on the surface soil moisture points represent plus and minus one standard deviation

During the first period, in the summer of 2002, continuous occult precipitation (fog and dew) was observed, but not reflected in the precipitation record, and may have contributed to the increase in near surface soil moisture. Previous studies have noted that occult precipitation is a significant source of water in the Barrow region and is often not recorded in the precipitation measurements (Dingman *et al.* 1980; Benson 1982; Yang *et al.* 1998). The second period, in the summer of 2003, was early in the season (mid-June). Over the six days between measurement dates the average ground heat flux was 13.8 W/m^2 and the average relative humidity was 87%. This indicates that the ground was a large sink for energy to melt ice near the surface and the vapor pressure deficit

(VPD) was low, inhibiting evapotranspiration. It follows that the water from ice melting near the surface in conjunction with the low VPD inhibiting evaporation rates may have led to the observed increase in near surface soil moisture without substantial precipitation inputs.

Spatial variability of soil moisture

Point measurements of near surface soil moisture were highly variable over the study period. Standard deviations for all 189 points on measurement dates ranged from 18% to 30%, with VWC at an individual measurement point ranging from a low of 14% to a high of 93% over the four years of the study (Fig. 4(a–d), Table 2). Even though the study area was small, the variability and range in near surface soil moisture was large. This range was greater than that reported by McFadden *et al.* (1998) at a 5 cm depth, for the five different tundra vegetation types (15–83%) found within the 9200 km² Kuparuk watershed on the North Slope of Alaska.

Relationship with topography

Inter- and intra-annual variations in near surface soil moisture were examined in relation to topography. Seasonal average near surface soil moisture values were calculated for each of the four microsite types (Table 2). In all four seasons, the troughs had the highest VWC, followed by featureless, then flat-centered polygons and high-centered polygons (Table 2). Within microsite types variability in seasonal average near surface soil moisture values was high in all four seasons with coefficient of variation (CV) values ranging from 10.9–24.5% (Table 2). Variability in the annual average near surface soil moisture was greatest in the featureless microsite type, having the greatest CV in all four years of the study (Table 2). This high variability of near surface soil moisture in featureless microsite types may be

Table 2 Descriptive statistics for the percent volumetric surface soil moisture for the four different microsities over the four years of the study

		Average	Minimum	Maximum	Standard deviation	Coefficient of variation
2000	n	(%)	(%)	(%)	(%)	(%)
Trough	30	72	58	87	7.9	10.9
Featureless	89	67	41	89	12.5	18.8
Flat-centered	34	62	37	81	10.1	16.3
High-centered	32	54	34	70	8.6	15.9
2001						
Trough	30	69	51	88	9.7	14.1
Featureless	89	64	28	88	14.1	22.0
Flat centered	34	58	35	79	10.8	18.3
High centered	32	50	28	72	10.4	21.1
2002						
Trough	30	68	41	87	10.2	15.0
Featureless	89	65	23	89	13.6	20.9
Flat centered	34	59	41	82	9.7	16.4
High centered	32	51	31	72	9.6	18.8
2003						
Trough	30	62	44	80	9.3	15.0
Featureless	89	59	28	82	14.4	24.5
Flat centered	39	54	34	76	10.5	19.7
High centered	32	45	26	65	10.6	23.3

attributed to the lack of a substantial polygonal structure, which would control the redistribution of near surface soil moisture to produce a more organized spatial pattern.

Differences in the mean annual values of near surface soil moisture values of the four microsite types were compared using an analysis of variance (ANOVA) with a *post hoc* Scheffe *F* test (Tabachnick and Fidell 1989). Results from the *F* test indicated that the means of troughs and flat-centered polygons, troughs and high-centered polygons, and featureless and high-centered polygons were significantly different at the 0.05 confidence level in the 2000, 2001 and 2002 seasons (Table 3). The means of the other three pairs, troughs and featureless, featureless and flat-centered polygons, and flat and high-centered polygons were not significantly different at the 0.05 confidence level in 2000, 2001 and 2002 (Table 3). In 2003, the results were similar, except the means of the troughs and flat-centered polygons were not significantly different at the 0.05 level. The lack of a significant difference between troughs and flat-centered polygons may be due to the low precipitation total in 2003. The summer of 2003 had the least amount of precipitation of all four years. In 2003, both troughs and flat-centered polygons had the lowest average near surface soil moisture (Table 2) and the smallest mean difference (Table 3), which may have yielded the non-significant difference result. Based on the overall results, the microsite types which have the greatest relief, high-centered polygons and troughs, were the only two types that apparently have significant control over the mean, near surface soil moisture.

Intra-seasonal variations in the average near surface soil moisture between microsite types were examined by plotting the values for each measurement date over the four years (Fig. 5(a-d)). The relative differences in near surface soil moisture between microsites types

Table 3 Results of the ANOVA, *post hoc*, Scheffe *F* test from all combinations of data for all four years

Year	Combination	Seasonal average surface soil moisture mean difference (%)	Significant difference
2000	Trough-Featureless	5.8	No
	Trough-Flat-centered	10.5	Yes**
	Trough-High-centered	18.0	Yes**
	Featureless-Flat-centered	4.8	No
	Featureless-High-centered	12.2	Yes**
	Flat-centered-High-centered	7.5	No
2001	Trough-Featureless	4.6	No
	Trough-Flat-centered	11.0	Yes**
	Trough-High-centered	19.2	Yes**
	Featureless-Flat-centered	6.5	No
	Featureless-High-centered	14.7	Yes**
	Flat-centered-High-centered	8.2	No
2002	Trough-Featureless	3.4	No
	Trough-Flat-centered	9.1	Yes*
	Trough-High-centered	16.5	Yes**
	Featureless-Flat-centered	5.7	No
	Featureless-High-centered	13.1	Yes**
	Flat-centered-High-centered	7.4	No
2003	Trough-Featureless	3.1	No
	Trough-Flat-centered	8.3	No
	Trough-High-centered	16.4	Yes**
	Featureless-Flat-centered	5.2	No
	Featureless-High-centered	13.4	Yes**
	Flat-centered-High-centered	8.2	No

Significance level 0.05* and 0.01**

were consistent throughout all four summer seasons (Fig. 5(a–d)). For all 30 measurement dates, troughs had the highest VWC followed by featureless areas, then flat-centered polygons, with high-centered polygons having the lowest VWC. The pattern of relative moisture content between troughs and high-centered polygons followed the expected pattern, with low areas being wetter and high areas being drier.

Differences in VWC between the flat-centered polygons and featureless microsite types may have been more a result of their topographic position in the landscape due to the macrotopography than to differences due to microrelief. Both the featureless and flat-centered polygon microsite types have very little microrelief (<0.25 m) (Hinkel *et al.* 2003). However, a large number of the featureless microsite types fell within lowland regions, characterized by drained thaw lakes (37 out of 89), while the majority (25 out of 34) of the flat-centered polygons were located in the upland portion of the study area. The

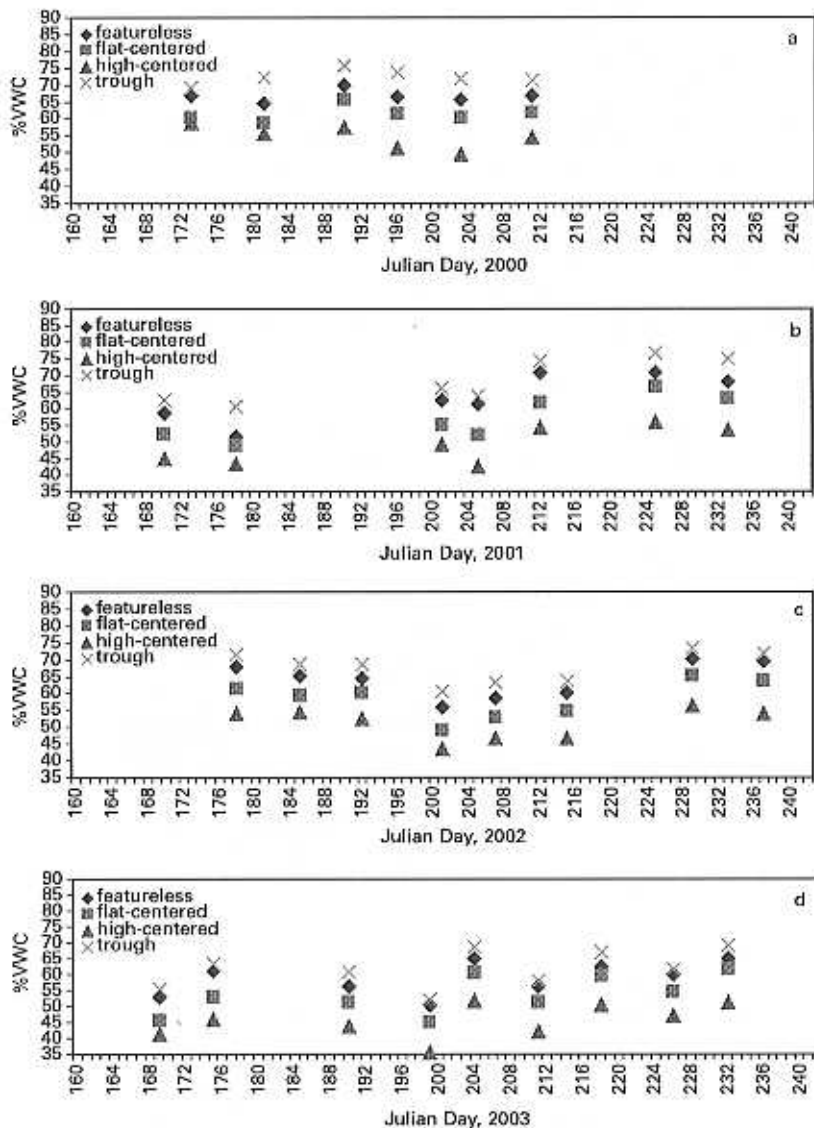


Figure 5 Average near surface soil moisture at the four microsite types in (a) 2000, (b) 2001, (c) 2002 and (d) 2003

drained thaw lakes have a lower relative topographic position in the landscape compared to the upland area (approximately 3–5 m). Thus, there is a lateral redistribution of water from the upland area into the lowland, drained thaw lakes areas. This may lead to an overall increase in average near surface soil moisture in the lowland areas relative to the upland area. Therefore, the redistribution of water associated with macrotopography may have produced the observed differences in near surface soil moisture values between the flat-centered and featureless microsite types.

The effects of macrotopography and relative topographic position in the landscape on the distribution of near surface soil moisture were investigated. This was done by spatially partitioning the intensively sampled data set into four regions representing upland and lowlands, then sub-dividing by microtopography. The resulting four regions were 1) the upland region with high-centered polygons and troughs ($n = 186$), 2) the upland region with flat-centered polygons and featureless areas ($n = 198$), 3) the lowland region with high-centered polygons and troughs ($n = 62$) and 4) the lowland region with flat-centered polygons and featureless areas ($n = 187$). These regions were identified by visual interpretation using high resolution (0.25 m^2) multi-spectral digital camera imagery, which was geo-referenced to the Hussey and Michelson (1966) map depicting lakes, the ages of drained basins and areas without evidence of thaw lake activity near Point Barrow, Alaska.

The median, quartiles and range in near surface soil moisture within the four regions, described above, are displayed in a box plot (Fig. 6). Near surface soil moisture was highly variable in all four regions (Fig. 6). As expected, near surface soil moisture in the two lowland groups was greater than the two upland groups. When comparing near surface soil moisture measurements between the upland and lowland regions, the maximum difference in the median near surface soil moisture was between the areas characterized by flat-centered polygons and featureless microsite types (Fig. 6). Differences in near surface soil moisture between the upland and lowland regions were greatest in the areas with flat-centered polygons and featureless microsite types compared to the high-centered polygons and trough microsite types (Fig. 6). Even though the maximum difference in elevation across the study area is only 5.5 m, relative topographic position in the landscape, as a result of

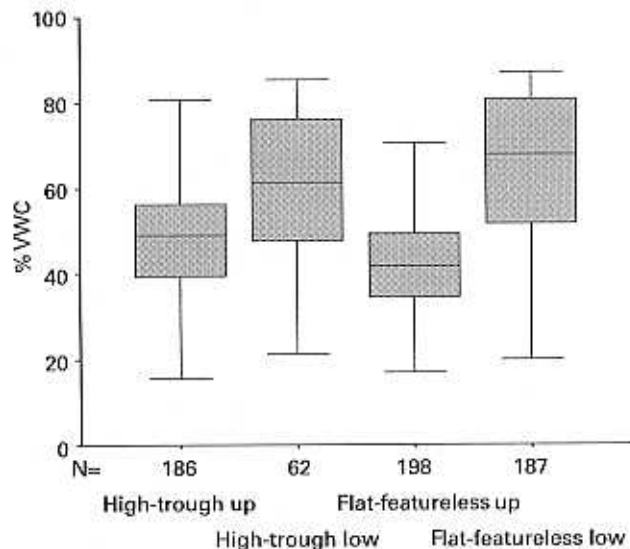


Figure 6 Box plots showing the median, quartiles and range of volumetric water content for the intensively sampled data subdivided into four categories: flat-featureless upland, flat-featureless lowland, high-trough upland, and high-trough lowland

macrotopography, has a large affect on the lateral redistribution of water and near surface soil moisture.

Summary and conclusions

The magnitude of both the temporal and spatial variations in soil moisture was high with changes in VWC of greater than 75% within a 0.5 km² study area. Even with the high spatial variability in near surface soil moisture the results indicated that the 189 samples collected along the seven transects were representative of the entire study area. As expected, precipitation appeared to be a major driver of intra-seasonal variations in near surface soil moisture values. In addition, the results indicate that melting ice and difficult-to-measure occult precipitation may influence near surface soil moisture values in this Arctic area.

Near surface soil moisture within an individual microsite type was highly variable both inter- and intra-seasonally. Despite this variability, the relative ranking of near surface soil moisture between microsite types was consistent both inter- and intra-seasonally. This indicates that microtopography had a substantial control over the spatial distribution of near surface soil moisture. Microtopography had a significant effect on the mean near surface soil moisture in areas with high-centered polygons and troughs. However, in areas without substantial microtopography (flat-centered and featureless microsite types), microsite type did not significantly affect the distribution of near surface soil moisture.

The controls over variations in near surface soil moisture occurred at multiple scales within the landscape. Over small areas (0–10 m²), microtopography was a substantial (and sometimes significant) organizer of near surface soil moisture, while over larger areas (10–100 m²), relative topographic position had a large effect on near surface soil moisture. This is evident when investigating the differences in near surface soil moisture between the flat-centered polygon and featureless microsite types. Both flat-centered polygons and featureless microsite types were not significant organizers of near surface soil moisture. However, flat-centered polygon microsite types were consistently drier than featureless microsite types for all 30 measurement dates over the four years of the study. The majority of the flat-centered polygon microsite types are located in the drier, upland region, while a large number of the featureless microsite types are located in the lower, wetter drained thaw lake regions. Thus, relative topographic position in the landscape, as a result of macrotopography, appears to be the major factor leading to differences in average near surface soil moisture between the flat-centered polygon and featureless microsite types.

The magnitude of the variability in near surface soil moisture observed in this study could have a significant impact on and should be considered when modeling fluxes of energy and carbon in the Arctic coastal plain. In order to model this variability, partitioning the landscape by microtopography may not be a viable approach in areas dominated by featureless and/or flat-centered polygons. Such an approach may be applicable in portions of the landscape dominated by substantial microtopography (high, low-centered polygons and troughs), i.e. approximately 65% of the land area in the Barrow region (Brown 1967). In study areas such as the one investigated here, a statistical dynamic approach may be a more applicable method for representing spatial variations in near surface soil moisture.

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