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SPATIAL AND TEMPORAL PATTERNS OF SOIL MOISTURE AND THAW DEPTH AT BARROW, ALASKA U.S.A.

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Abstract

Data on active-layer thickness and near-surface soil moisture content were collected in late summer 1996 and 1997 at 100-m intervals over a 1 km^2 area near Barrow, Alaska. Thaw depth and soil moisture data were mapped to facilitate interannual comparisons and to evaluate the effects of terrain and parent material on moisture content. Statistical analysis indicates that: (1) substantial differences in soil moisture and thaw depth occur in dissimilar terrain units; (2) soil moisture and thaw depth are relatively uniform within terrain units; (3) spatial patterns of thaw depth are consistent within the study area on an interannual basis; and (4) patterns of soil moisture and thaw depth do not necessarily show close spatiotemporal correspondence. Time series of soil moisture show large variations near the surface in response to precipitation and evaporative drying, but the lower part of the active layer remains near saturation throughout the summer.

Introduction

The quantity of water present in the soil influences many processes including gas exchange with the atmosphere, diffusion of nutrients to plant roots, and the speed with which solutes move through the root zone (Jury et al., 1991). In the active layer above permafrost, the amount of soil moisture present influences the development of ground ice, thereby exerting an important influence over terrain evolution. Moisture content also affects soil temperature and the thermal properties of the active layer and permafrost, with attendant implications for modeling (Waelbroeck et al., 1997).

Precision measurement of soil water content has long been impeded by a lack of efficient and nondestructive methods of instrumentation. This is especially true in the Arctic, where instrumented sites are often remote and the presence of permafrost can make sensor installation difficult. Although Time Domain Reflectometry (TDR) and gravimetric methods have been used successfully in permafrost environments (e.g., Stein and Kane, 1983), both methods have limitations. TDR is expensive and provides measurements only at point locations. The gravimetric method is labor intensive, locally destructive, and is not conducive to intensive spatial sampling (Crave and Gascvel-Odonx, 1997).

The literature relating the spatial distribution of soil moisture to that of active-layer thickness is not voluminous. Such data were collected by the U.S. Army's Cold Regions Research and Engineering Laboratory (USA CRREL) in the early 1960's along a transect at Barrow, Alaska (Brown and Johnson, 1965; Brown, 1969). The sampling program was designed to traverse several terrain units described later in this paper. The thickest active layers were associated with relatively warm summers and high precipitation. Dry, coarse-grained soils experienced deeper thaw than moist soils with finer texture and higher organic content. Subsequent investigations 25 years later (Nelson et al., 1998) in the same terrain units near Barrow found deep thaw in well-drained coarse sediments, and thinner active layers in a drained lake basin and a nearby upland with well-developed ice-wedge polygons. Two-dimensional correlograms for the soil moisture and thaw-depth fields at Barrow displayed a high degree of correspondence.

The apparent relation between the thickness of the active layer and major terrain units suggests that thaw depth is a categorical response to land-cover characteristics. Soil moisture, in particular, appears consistently as an important factor. This paper reports a program concerned with (1) obtaining spatially extensive samples of near-surface soil moisture, (2) creating mapped fields from the sample data, and (3) comparing the spatially referenced soil moisture data with information on parent material, topography, and active-layer thickness at the same locations.

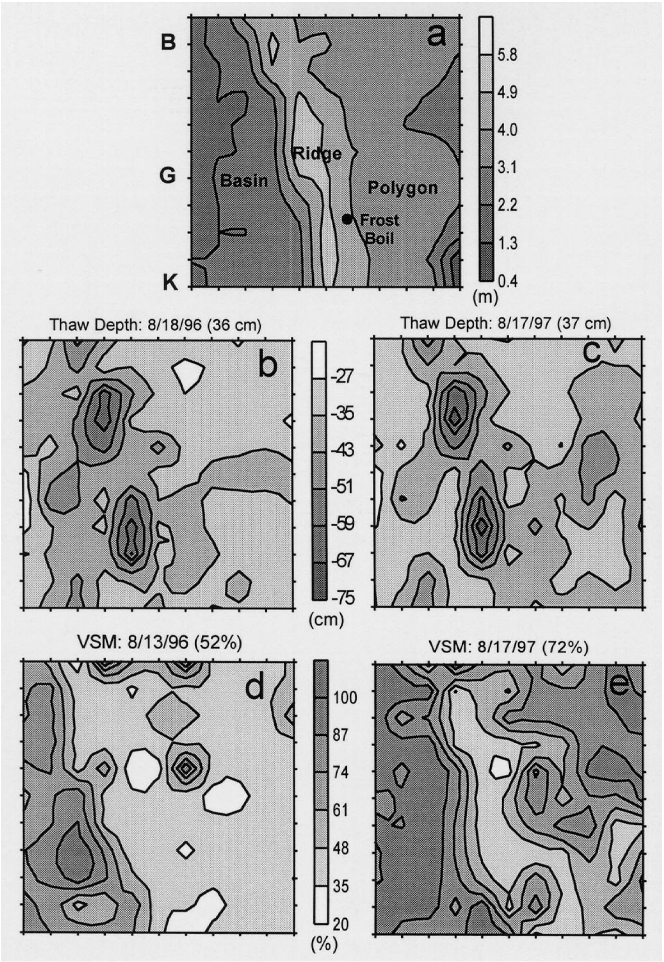

Figure 1. Study area on Barrow 1 km^2 ARCSS grid. Tick marks at 100-m intervals and intersections represent sampling locations. Maps show (a) elevation (m) and terrain units; (b) maximum thaw depth for 18 August 1996 and (c) 17 August 1997; and volumetric soil moisture content for (d) 13 August 1996 and (e) 17 August 1997. Values in parentheses are the grid averages; dot shows location of frost boil.

Site description and methods

Soil moisture content and end-of-season active-layer thickness ("thaw depth") were measured during late August over a 1 km^2 area in the Barrow Environmental Observatory near Barrow, Alaska (71°19′ N, 156°35′ W). This area currently serves as a research site for the U.S. National Science Foundation's Arctic Systems Science/Land-Atmosphere-Ice Interactions (ARCSS/LAII) program, as one of the primary International Tundra Experiment (ITEX) locations, and as one of the main observation sites for the Circumpolar Active Layer Monitoring (CALM) program (Brown et al., 1997). The area is subdivided into 1-ha cells defined by a network of steel stakes located at 100 m intervals. The 121-stake network, referred to subsequently as the Barrow "ARCSS grid," was surveyed to a high order of accuracy (±10 cm) and is tied into the Universal Transverse Mercator coordinate system. The grid partially overlaps the transect employed by USA CRREL researchers during the 1960's.

The Barrow ARCSS grid contains three major topographic units (Figure 1a). These include a drained basin (Central Marsh) in the western part, a north-south trending beach ridge formed during a marine regression in late Wisconsinan time (Brown et al., 1980), and an area of upland tundra dominated by ice-wedge polygons. Central Marsh is the site of a former lake or lagoon, and the fine-grained soils within it are usually wet during summer. The beach ridge comprises the highest elevations in the study area (~6 m) and is composed of reworked sand and gravel overlain with a thin veneer of fine sediment. The polygonised upland has slightly higher elevation than Central Marsh and is better drained. Low-centred ice-wedge polygons occupy the northern part of this area, whereas high-centred polygons dominate the southern part (Brown and Johnson, 1965; Brown, 1969).

Active-layer thickness and soil moisture were measured in August of 1996 and 1997 at each of the grid nodes, except those at which the presence of gravel or deep standing water prevented measurement. Thaw depth was determined by inserting a 1-cm diameter steel rod to the point of resistance. Two observations were made within 1 m of each of the grid stakes; the average is reported in this paper (Figure 1, Table 1).

The analysis of soil moisture was enabled by development of a new generation of soil-moisture sensors, the "Hydra Soil Moisture Probe"®, manufactured by Vitel, Inc. This compact (2.5-cm diameter) sensor determines the complex dielectric constant of soil using frequency-domain techniques based on four voltages, which are measured between the instrument's 10-cm tines. A built-in thermistor determines temperature, which is

Table 1. Descriptive statistics for active-layer thickness (cm) and volumetric soil moisture content (%) for entire ARCSS grid and for terrain-based subgroups. Sampling dates are given in text and Figure 1 caption. Pearson product-moment correlation coefficients between means for 1996 and 1997 are shown in right-hand column

Maximum Thaw Dept	N	Mean	Std. Dev.	Corr. Coef.
1996	119	35.6	8.5	0.85
1997	117	36.8	9.3	
Basin 1996	41	36.4	7.2	0.89
Basin 1997	41	33.5	7.0	
Ridge 1996	17	44.8	14.4	0.96
Ridge 1997	17	47.9	15.7	
Polygons 1996	61	32.5	4.1	0.59
Polygons 1997	59	35.9	5.2	

Soil Moisture	N	Mean	Std. Dev.	Corr. Coef.
1996	118	51.6	18.9	0.62
1997	118	72.1	21.6	
Basin 1996	41	68.4	15.4	0.22
Basin 1997	41	89.0	10.9	
Ridge 1996	16	36.9	6.8	0.43
Ridge 1997	16	42.4	6.9	
Polygons 1996	61	44.3	14.9	0.43
Polygons 1997	61	68.5	19.3	

used to correct values of the complex dielectric constant. The manufacturer supplies a program to convert the output voltages to temperature-corrected complex dielectric constants, and derives a volumetric estimate of soil moisture content. The user provides categorical information about soil texture which serves to refine the estimation of moisture content. Sensors from various manufactured batches have been used by USDA-NRCS and CRREL technicians to evaluate the overall performance for monitoring soil moisture and temperature during long-term field operations. Comparison between sensor and gravimetric measurements in a variety of soils including organics indicate agreement to within several percent. Testing is continuing, but the preliminary results are encouraging.

To obtain high-frequency time series of soil moisture in the vicinity, four soil-moisture sensors were installed vertically in a frost boil in the southern part of the polygonised area (Figure 1a). These sensors were attached to a Campbell CR10 data logger and, beginning in June 1996, measurements were made hourly at depths of 10, 25, 40 and 55 cm.

Spatially extensive measurements were made by mounting a single Vitel sensor on steel conduit and connecting it to a standard voltmeter. In this "portable mode," soil moisture was measured within a few decimeters of the grid node stake by vertically inserting the sensor tines into the soil. The voltages were recorded on cassette tape and the data later transcribed for digital processing. The reported soil moisture is a depth-averaged value for the upper 10 cm; values approaching 100% represent readings taken in saturated or submerged organic-rich surface materials.

Data presentation and analysis

GENERAL SPATIAL PATTERNS AND INTERANNUAL COMPARISONS

The effect of the three topographic units is evident in the spatial patterns of thaw illustrated in Figures 1b and 1c. Greater thaw depths are associated with the beach ridge. Furthermore, the active layer shows a consistent pattern of thaw from one year to the next, with only minor interannual differences. Descriptive statistics are shown in Table 1; the average annual thaw depth (36 cm) and standard deviation in 1996 and 1997 are statistically indistinguishable. The Pearson product-moment correlation coefficient of 0.85 between the 1996 and 1997 data sets, and results from a paired t-test ($p<.001$), confirm the high degree of thaw pattern similarity between the two summers. This result is consistent with those of Nelson et al. (1998), who used spatial autocorrelation analysis to demonstrate that interannual patterns of thaw at sites on the coastal plain are replicated from year to year.

The two maps of soil moisture are shown as Figures 1d and 1e. The spatial patterns are generally similar, with the wet basin and polygonised upland areas separated by drier beach ridge. Overall, there is an increase in the mean volumetric soil moisture content by about 20% between 1996 (52%) and 1997 (72%); the correlation coefficient between the 1996 and 1997 values is 0.62. The wetter conditions at the time of sampling in 1997 were manifested in the field as extensive areas of shallow standing water, particularly the area of low-centred polygons in the northeastern quadrant of the map. This area of the map also experienced greater thaw depths in 1997.

An explanation for this difference is the greater amount of precipitation during the summer of 1997. Summer rainfall for 1996, reported by the National Weather Service station at Barrow (~5 km north of grid), totaled 52.6 mm. The 1997 total was 96 mm, making it the second wettest summer on record (D. Endres, personal communication). Of this, 67.1 mm (~70%) fell during August.

TERRAIN-SPECIFIC DIFFERENCES

To investigate the effects of terrain and parent material on thaw depth and soil moisture, the data from the study area were subdivided into three groups representing the primary terrain units (Table 1). About 34% of the grid nodes were within the basin, 14% were collected on the beach ridge, and 52% were sampled in the polygonised upland. Descriptive statistics for each of the subgroups are shown in Table 1.

In both years, the beach ridge experienced maximum thaw depths and largest variability. The polygonised upland and drained basin have values close to the grid mean, although there was less variation in the polygonised area. Note the high degree of interannual (1996-97) correlation of thaw depth in the basin (0.89) and ridge (0.96) subgroups.

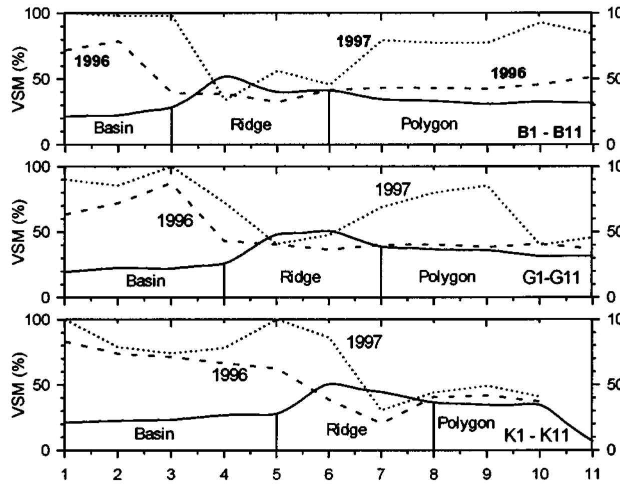

Figure 2. Comparisons of soil moisture content along transects on mid-August sampling dates in 1996 (dashed line) and 1997 (dotted line). Elevation profiles are shown to facilitate comparison with terrain units.

In a similar manner, soil moisture in the beach ridge (~40%) is significantly less than the average over the entire grid, and experiences relatively little areal or interannual variation. Conversely, the basin consistently has the wettest soil, exceeding the spatial average by about 17% each year. The polygonised area has intermediate values and a large degree of scatter about the mean. This area, in particular, was observed to be much wetter in late summer 1997.

To further illustrate the effect of terrain and parent material on soil moisture, three west-east transects are plotted as Figure 2. From north to south, these are labeled, B1-B11, G1-G11, and K1-K11, as shown in Figure 1a. The graphs show soil moisture content for 1996 and 1997, and elevation in decimeters. In all three transects, lower values of soil moisture content are associated with the beach ridge, reflecting the influence of coarse sediments on water drainage.

As would be expected, the low-elevation basin has consistently highest moisture content. Two patterns are noted. First, soil moisture content increased throughout the basin in 1997. Second, the basin-beach ridge boundary is displaced eastward in 1997, up the beach ridge. This probably reflects higher water levels in the wet summer, and an expansion of wet conditions within the basin.

The maximum interannual difference is observed in the region of low-centred polygons in the northeast quadrant of the ARCSS grid, as exemplified by the B1-B11 and G1-G11 transects. Here, large areas of standing water were observed covering the entire surface of the polygons except for the raised polygon rims. In the southeast part of the grid (K1-K11), the prevalence of high-centred polygons promoted runoff through the network of troughs over the degraded ice wedges, and soil moisture values were only slightly higher than on the sampling date in 1996.

TEMPORAL PATTERNS

Figure 3 illustrates the temporal patterns of soil moisture within a frost boil during summer 1997. Hourly values from 15 June to 15 August are graphed as traces for depths of 10, 25, 40 and 55 cm. Significant rain events, recorded at the Barrow NWS station, are shown as vertical bars. At the beginning of the record, the ground was still frozen. The thaw front reached the 10-cm level around 20 June, and is apparent as a steep increase in soil moisture content as ice is converted to water. A similar pattern is observed at the 25-cm level in late June, and at 40 cm in early July. The relatively thick active layer (>55 cm) at this location is probably attributable to the lack of vegetation cover on the surface of the frost boil.

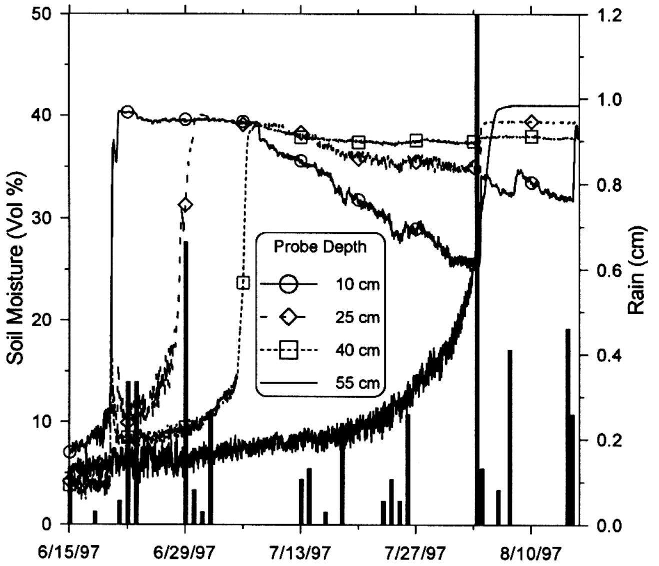

Figure 3. Time series of volumetric soil moisture content (%) from frost boil in Barrow ARCSS grid. Hourly values at 10, 25, 40 and 55 cm are shown as traces. Bars represent daily precipitation (cm) from NWS installation in Barrow.

The soil remained nearly saturated around 40% from recharge until mid-July. This was followed by a dry period which caused a reduction in soil moisture; the effect was maximised at the surface but had only minimal impact at depth. A substantial rainfall event on 3 August (1.2 cm) caused the steep ascensions in the traces, with soil moisture content increasing about 10% at the 10-cm probe level and about 5% at the 25-cm probe. Evaporative drying in August is limited by sporadic rainfall events correlated to inflections apparent on the 10-cm trace. These patterns are similar to those documented by Hinkel et al. (1993; 1997) and Hinkel and Nicholas (1995). In those studies, sporadic rain events were shown to accelerate the rate of thaw, particularly in coarse sediments with high infiltration capacity.

Discussion

Active-layer thickness is influenced by several variables including air temperature, terrain-induced contrasts in microclimate, thermal buffering by the vegetation cover, residual effects from the previous winter's snow cover, the thermal properties of the substrate, and soil-moisture conditions. Despite this complexity, many investigators (e.g., McRoberts, 1975; Hinkel and Nicholas, 1995; Mackay, 1995; Nelson et al., 1997) have shown that the annual progression of active-layer thickness at point locations or within small homogeneous areas can be described by a simple relation based on the square root of thawing degree-day accumulation. This nearly universal relation demonstrates that active-layer development is an integrated and relatively long-term (seasonal) response to a combination of physical and biological processes, some of which can fluctuate substantially (or even have opposing effects) over shorter time scales.

At several sites on the coastal plain, Nelson et al. (1998) found that wet soils in drained thaw-lake basins experienced deeper thaw than did drier, fine-textured soils in the intervening uplands. Nelson et al. (1997) stratified a 28,000 km^2 area of the North Slope by land-cover unit and computed active-layer thickness to an accuracy of about 10% of measured values within several 1 km^2 test plots. The land-cover units employed were strongly associated with terrain features in the coastal plain. Soils associated with the "wet tundra" landcover category in the Kuparuk River basin (Auerbach et al., 1996) experienced greater depths of thaw than any of the other categories involving significant amounts of vegetation cover. Drained thaw-lake basins are the primary terrain unit in which saturation is maintained throughout the thawing season. Under such conditions, water-filled soil pores provide the entire soil layer with relatively high values of thermal conductivity. This apparently increases the heat flux to depth and promotes deeper thaw, despite that fact that a larger proportion of the surface energy budget is diverted to latent heat. The impact of vegetation and parent material can be appreciated by noting that the thickest (> 1 m) active layers in the Kuparuk basin were found in coarse alluvial deposits with discontinuous vegetation cover (Nelson, unpublished data).

Figure 3 demonstrates that near-surface soil moisture can fluctuate at relatively high temporal frequencies. This situation is particularly likely at sites with good drainage and in soils with high infiltration capacity. During periods of dry weather, the near-surface soil layer at such sites loses moisture and becomes, in effect, an insulating layer that retards heat flux to depth.

An intermediate situation develops in wet summers in locations represented by the northeast section of Barrow ARCSS. If soils remain saturated over extended periods, water accumulates at the surface and the thermal regime resembles that in the basin. The largest interannual differences in active-layer thickness appear to occur in such situations; the depth of thaw in the basin is large but fairly constant on an interannual basis, whereas better-drained upland sites can experience large interannual differences in response to interannual changes in the soil moisture regime. An analogous situation was observed in the summers of 1995 and 1996 at the West Dock ARCSS grid near Prudhoe Bay (Nelson et al., 1998).

Conclusions

The ARCSS grid at Barrow, which contains a representative sample of local terrain units in this part of the

Alaska's arctic coastal plain, experiences large variations in soil moisture over both space and time. Extensive measurements over the grid demonstrate that near-surface variations, in particular, are substantial. Intensive observations at the frost boil location indicate that, despite high temporal variability at shallow depth, moisture content near the base of the active layer can remain relatively constant.

The thickness of the active layer is an integrated response to several important variables and generally conforms to a simple relation with the square root of the thawing index. The slope of this relation is governed by interrelated site- and time-specific factors, of which soil moisture is one of the more important. End-of-season thaw depth is, however, a time-integrated, cumulative response to conditions occurring over the course of the thaw season. By contrast, measurements of soil moisture represent a time-specific "snapshot" of a dynamic fluctuating system, particularly near the surface of well-drained soils. There is little reason to expect, therefore, that a close correspondence should exist between the late-summer depth of thaw and near-surface moisture conditions on a single sampling date. A strong statistical relationship is more likely to exist between the depth of thaw and average seasonal values of soil moisture at representative locations.

The results of this study support a conceptual model in which active-layer thickness can be regarded as a categorical response to seasonal regimes of temperature and precipitation (Nelson et al., 1997; 1998). Terrain units that ordinarily experience near-saturated conditions, such as drained thaw-lake basins, are buffered from substantial interannual variations of active-layer thickness if temperature regimes are similar. Coarse-grained sediments with extremely good drainage, typified by the beach ridge at Barrow, can exhibit a strong response to both seasonal temperature regimes and precipitation. Large interannual fluctuations in thaw depth can occur in terrain units with silt-textured soils that are well-drained in dry years but become waterlogged for extended periods in summers with high precipitation.

Acknowledgments

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