SPATIAL AND TEMPORAL ATTRIBUTES OF THE ACTIVE-LAYER THICKNESS RECORD, BARROW, ALASKA, U.S.A.

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Abstract

Active-layer thickness was measured during the periods 1962-1968 and 1991-1997 in a series of 19 plots representing different landcover and terrain characteristics near Barrow, Alaska. Mean values in the 1960’s were generally higher than in the 1990’s. Climate Matrix Analysis (CMA) reveals strong internal consistency in the active-layer data. Plotted for the entire record, considerable scatter exists in the relation between active-layer thickness and the square root of the thawing index. Partitioning of the data into interdecadal segments, however, reveals very strong relations between these variables. This discrepancy may be an artifact of interannual or interdecadal variations in soil moisture, ice content in the uppermost permafrost, ground cover characteristics, and/or nonconductive heat-transfer processes. The Barrow active-layer record illustrates the value of systematic, long-term observations of thaw depth, currently being performed under the Circumpolar Active Layer Monitoring (CALM) program.

Introduction

Barrow, Alaska (71° 18’ N, 156° 47’ W) has been a center of permafrost-related research since the inception of the Naval Arctic Research Laboratory in the late 1940’s (e.g., Brewer, 1958; Drew et al., 1958; Lachenbruch, 1959; Kelley and Weaver, 1969). Situated at the confluence of the Beaufort and Chukchi Seas, the absence of erect shrubs at mesic sites in the Barrow Peninsula indicates its proximity to the southern boundary of the High Arctic Tundra subzone. Wet sedge meadows cover a landscape dominated by ice-wedge polygons and revegetated, oriented thaw lake basins of varying age (Britton, 1957; Carson and Hussey, 1962; Brown, 1967). Mean annual temperature is -12.6°C and measured precipitation averages 12.4 cm/yr. A steep climatic gradient exists near the coast (Clebsch and Shanks, 1968). Extrapolation of borehole temperatures indicates that permafrost thickness in the area exceeds 400 m (Lachenbruch et al., 1988). A recent study by Waelbroeck et al. (1997) used geocryological and ecological data from Barrow to model relations between active-layer thickness and carbon dynamics over time.

In 1962, the U.S. Army’s Cold Regions Research and Engineering Laboratory (CRREL) initiated a research programme that included sampling thaw depth at a series of plots chosen as representative of landcover and terrain characteristics near Barrow (Brown and Johnson, 1965; Brown, 1969). That programme ended in 1968 and measurements at the CRREL plots were made in only the first year of the 1970-74 IBP Tundra Biome project at Barrow (Brown et al., 1980). At the conclusion of the 1960s observations, it was assumed that they contained the minimum and maximum mean thaw depth for the period of climate record at Barrow (1921 to present). However, resumption of the observation programme in the 1990’s refuted this supposition. Annual observations at the CRREL sites were resumed in 1991 as part of the Arctic Systems Science/Land-Atmosphere-Ice Interactions (ARCSS/LAII) program, supported by the U.S. National Science Foundation. The area in which measurements are made is part of the recently established Barrow Environmental Observatory (BEO), an area set aside and protected for research by the Ukpeagvik Inupiat Corporation (inset, Figure 1). The observations reported here are a contribution to the Circumpolar Active Layer Monitoring (CALM) program, a coordinated effort operated on a voluntary basis by permafrost researchers at some 70 locations in ten countries (Brown, 1997). The set of standardised monitoring procedures employed at many of these sites is detailed in the ITEX (International Tundra Experiment) Manual (Nelson et al., 1996).
Sampling design

Beginning in 1962, the thickness of the active layer was determined in the CRREL plots, which are distributed along a transect between Central Marsh and Elson Lagoon (Figure 1). The sampling design was discussed in detail by Brown and Johnson (1965). Each 10 x 10 m plot was marked with a permanent stake, and 36 sampling points were delimited with a series of secondary markers. Measurements were made with a 1.0 cm diameter steel rod pushed into the soil to the point of refusal. Comparison of paired observations obtained by this method with thermal determinations made at nearby (~10 cm away) points indicate no significant differences in this vicinity (Nelson, unpublished data).

To minimise disturbance to the plots, measurements were initially made at weekly intervals near the outermost 20 points, with end-of-season determinations also made near the interior 16 markers. Observations were made at small staggered distances from the markers to avoid a cumulative impact at the sampling locations. Although measurements were made at weekly intervals during several years in both decades, the record for most years contains only a single set of late-summer observations. Data summaries for 1962-68 and 1991-97 are available on the IPA’s Circumpolar Active-layer Permafrost System (CAPS) compact disc, compiled and distributed by the National Snow and Ice Data Center in Boulder, Colorado. The combined end-of-season average value for all of the CRREL plots is in close agreement with the average value for 121 sampling points on the 1 km² ARCSS/LAII grid at Barrow, which partially overlaps the CRREL transect (Figure 1; Nelson et al., 1998).

Analysis

Haugen et al. (1983) employed data from a sparse and irregularly distributed climate observation network to estimate temperatures in a remote region of northern Alaska. The technique used in that study, Climate Matrix Analysis (CMA), is easily adapted to problems involving active-layer thickness. A matrix consisting of data elements with temporal (climatic time series) and geographic (location) coordinates is constructed, and operations are performed for either or both of two purposes: (1) to produce estimates of missing elements in the matrix; and (2) to assess the degree of the internal consistency of data values in the matrix with respect to the set of spatial/temporal coordinates. Because
active-layer data from the CRREL plots were not collected for 20 consecutive years (1971-1990), only the second CMA function is pursued in this study, and estimation of values for missing cells was not attempted.

In the present analysis, the “climate” matrix X (Table 1) consists of an m x n array of (late summer) active-layer thickness observations $x_{i,j}$, where $i$ is a temporal index for the $m = 13$ years covered in the data set, and $j$ is a “geographic” index referencing the $n = 19$ plots included in the study. Stated alternatively, $x_{i,j}$ represents the mean value of active-layer thickness in year $i$ at CRREL plot $j$.

An $m$-element “temporal vector” $C$, with elements $c_i$ defined by

$$c_i = \sum_{j=1}^{n} x_{i,j} / n$$

is depicted in the right-hand column of Table 1. An $n$-element “geographic vector” $G$, with elements $g_j$ obtained by

$$g_j = \sum_{i=1}^{m} \left( x_{i,j} - c_i \right) / m$$

appears as the lowermost row in Table 1.

To assess the internal consistency (degree of spatial/temporal covariation) in $X$, the elements $r_{i,j}$ of a residual matrix $R$ are defined as

$$r_{i,j} = X_{i,j} - \left( c_i + g_j \right)$$

The “unexplained” variance $V_u$ resulting from the CMA, expressed in per cent, is defined as

$$V_u = (\text{var } R / \text{var } X) \cdot 100$$

The “explained” variance $V_e$, given by

$$V_e = 100 - V_u$$

provides a goodness-of-fit type index indicating the degree of consistency in the spatial/temporal array. Values of $V_e$ close to unity indicate a high level of covariation between the elements of $X$, and that individual $x_{i,j}$ can be predicted accurately from others. This result has important implications for efficient sampling. If $V_u$ is reasonably large (e.g., $\geq 80\%$), missing elements can be replaced by their estimated values ($c_i + g_j$); this is the approach used by Haugen et al. (1983). Climate Matrix Analysis can also be used as a check on the internal consistency of complete matrices. Large residual elements may indicate measurement or transcription errors, or a physical effect such as station relocation. Large values ($>20\%$) of $V_u$ indicate that the method is not suitable for a particular data set. This situation can arise through application of the technique to climatically heterogeneous data sets, such as those arising in complex terrain.

**Discussion**

For the Barrow data, CMA yields $V_e = 90.8\%$, indicating a high degree of internal consistency in the data matrix. Large residuals arise in most years for Plots 16 and 19 because these locations occupy a small drainage line in which soil moisture conditions are variable.
Annual values of active-layer thickness and the thawing index (degree-day accumulation above 0°C) are shown as a scattergram in Figure 2. There is considerable deviation from the close correspondence that has often been found between empirical data and simplified versions of the Stefan equation, one of which is given by

\[ Z_{al} = \beta DDT^{1/2} + a \]  

[6]

a regression-type equation in which \( Z_{al} \) is active-layer thickness (m), DDT is the seasonal thawing index (°C days), \( \beta \) represents the rate of thaw, and \( a \) is an intercept (Hinkel and Nicholas, 1995). The large degree of dispersion in Figure 2 plot indicates that the record of thaw depth at Barrow cannot be explained effectively by an examination of only the above-ground temperature record.

When data sets from the 1960’s and 1990’s are considered independently, as shown by the solid lines (obtained from Eq. (6)) in Figure 2, they are consistent with the Stefan relation. This artifact indicates that one or more of the parameters represented by \( \beta \), which include soil thermal properties, moisture conditions, latent heat, and above-ground biomass may “reset” the active layer to a new regime that is continued for several years. Stated alternatively, the active layer may exhibit Markovian behaviour.

Several possibly complementary hypotheses may account for the differences between the 1962-68 and 1991-97 series:

1. Ice segregation occurs preferentially at the bottom of the active layer in situations where two-sided freezing takes place (Williams and Smith, 1989, pp. 235-236); repeated on a year-to-year basis, an ice-rich zone develops, and is readily apparent in the stratigraphy of the active layer and upper permafrost (Brown and Sellmann, 1973; Estabrook and Outcalt, 1984; Shur et al., 1995). The large latent heat necessary to thaw this “buffer” layer inhibits rapid thaw, even in warm years, and tends to govern the thickness of the active layer. However, in a climatically extreme year the active layer may not reach the ice-rich zone, and ice segregation will occur at a new level that tends to govern the thickness of the active layer in subsequent years. Similarly, a series of relatively warm years could thaw the ice-rich layer and reset the active layer at a position deeper in the soil.

2. The shallow annual depths of thaw in the early 1990’s could be related to changes in the thermal properties of near-surface, organic-rich soils. Miller et al. (1998) and Nelson et al. (1998) found that the largest relative interannual changes in active-layer thickness on the coastal plain occurred in areas of low-centred ice-wedge polygons that experience substantial variations in soil moisture content. Oechel et al. (1995) reported a decrease in soil moisture, based on data from the nearby IBP Tundra Biome study area (Brown et al., 1980) between the 1970’s and 1990’s. In a related study (Hinkel et al., 1996), comparison of the ice content in cores from the CRREL plots in the 1960’s and 1990’s indicated an increase in the ice content of the upper permafrost.

3. Evidence exists that fusion and conductive heat transfer are not sufficient to explain interannual variations in active-layer thickness at Barrow (Outcalt et al., 1998). Field experiments and modeling have demonstrated that internal evaporation can retard the advance of the thaw front at midday (Outcalt and Nelson, 1985). There is significant interannual variability in the evapotranspiration component of the water balance in the Alaskan tundra (Dingman et al., 1980). Analysis of a conduction/fusion model of mean annual temperatures compared with field observations indicates that internal evaporation can significantly cool the active layer adjacent to the frost table (Outcalt et al., 1998).

4. Schultz (1964) suggested an ecological hypothesis for quasi-periodic behaviour in active-layer thickness. Schultz observed that the active layer at Barrow remained relatively thin over the course of several summers in the late 1950’s following a deep thaw in 1956 that coincided with a peak in the local lemming population. The proposed association, part of the “nutrient-recovery hypothesis,” involved intense grazing, reduction of insulation, and a thick active layer during years...
with large lemming populations. Nutrients supplied during periods of population peaks fertilize the tundra, so that insulation increases markedly in subsequent years, reducing the thickness of the active layer until the next major buildup in the lemming population. Similarly, Moen et al. (1993) observed substantial decreases in both graminoids and mosses during periods of peak lemming activity. There were no studies of lemming populations in the 1990’s at Barrow, but large quantities of plant litter (“mulch”) were observed at both the IBP and CRREL sites in 1991 and 1992, when active-layer thickness was at its minimum values.

Conclusions and recommendations

Consistent active-layer measurements at Barrow, covering the period 1962-68, yielded mean values between 31 and 43 cm. Re-establishment of the programme in the early 1990’s began with very low mean values (22-28 cm), and gradually increased to reach the lower part of the 1960’s range.

Analysis of the active-layer record at Barrow points to several tentative conclusions:

(1) The close covariation between plots with dissimilar ground cover, microtopography, and soil characteristics indicates that continuation of intensive sampling at all of the CRREL plots may not increase the yield of information on geographic variation substantially. For future monitoring programmes elsewhere, intensive exploratory sampling is necessary at new observation sites to determine the scale(s) of maximum variability and an appropriate sampling design for ongoing monitoring. In subsequent years, however, accurate results can be obtained by monitoring a carefully chosen subset of the original observation locations. At the Barrow CRREL site, the component of variance attributable to climate can be detected by confining measurements to those plots containing the extreme and mean thaw depths. This interpretation is in partial accord with results reported by Pavlov (1998) in West Siberia and by Nelson et al. (1998) from several locations on the North Slope, although the temporal database was of much shorter duration in the latter study. If substantiated further, this tentative conclusion has very positive implications for ongoing monitoring studies on active-layer thickness.

(2) Spatial analytic and process-oriented research at Barrow (Miller et al., 1998; Nelson et al., 1998; Outcalt et al., 1998) indicates that interannual variations in active-layer thickness are controlled by several factors, including soil moisture, vegetation, and nonconductive heat-transfer processes. Additional effort should be given to evaluating internal evaporation effects using micrometeorological investigations and the historical record of standard climatic variables (dew point, wind speed) that limit the magnitude of evapotranspiration.

(3) Data obtained from well-designed sampling experiments involving active-layer thickness, exemplified by the CRREL data-collection effort of the 1960’s, have considerable value for ongoing process-oriented investigations, as well as for climate-change studies. Establishment of the Circumpolar Active Layer Monitoring (CALM) network has expanded the global active layer database substantially and links it with existing archives devoted to other components of the cryosphere.

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References


