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Estimating Active-Layer Thickness over a Large Region: Kuparuk River Basin, Alaska, U.S.A.

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Abstract

Active-layer thickness was mapped over a 26,278-km^2 area of northern Alaska containing complex and highly variable patterns of topography, vegetation, and soil properties. Procedures included frequent probing to ascertain thaw depth in representative land-cover units, extensive thermal monitoring with data loggers, and application of spatial analytic techniques. Geographic information systems technology was used analytically to merge thaw-depth and temperature data with a digital land-cover map, a digital elevation model, and a topoclimatic index, yielding a spatial time series of active-layer thickness for the map area at weekly intervals over the summer of 1995. Although the maps show a strong regional trend in the thickness of the active layer, extreme local variation occurs in complex terrain and in areas with sharp discontinuities in soil moisture content. Because active-layer thickness is influenced strongly by vegetation and soil properties, the relative volume of thawed soil beneath several landscape units is not proportional to the relative surface area occupied by those units. Predicted values of active-layer thickness are within approx. 6 cm of measured mean values in representative 1-km units distributed over the latitudinal extent of the study area. If computed and averaged for a series of years (e.g, one decade), the integrated products yielded by the mapping procedures could be used as baseline documents for comparison with calculations based on climate-change simulations.

Introduction

Fluxes of greenhouse gases in the high latitudes are related to the thickness and moisture content of the active layer (Vourlitis et al., 1993; Oechel and Vourlitis, 1994). Most climate-change scenarios predict that global warming will be amplified in the polar regions, and available evidence indicates that a geographically variable but distinct increase in the temperature of lowland permafrost has already occurred (Fitzharris et al., 1996). Widespread thickening of the active layer (Kane et al., 1991) could increase the amount and variability of CO_2 emissions from tundra regions over the short term, possibly followed by an increase in carbon accumulation (Waelbroeck et al., 1997). Recent studies indicate that the arctic tundra may have changed from a net sink to a source of carbon dioxide, at least regionally (Oechel et al., 1993, 1995). Gilmanov and Oechel (1995) estimated the reserve of organic matter in the near-surface soil layer of the North American and Greenlandic tundra biome at 70 to 100 Gt, a figure that does not include the large quantity of carbon stored in the upper layer of the permafrost (Michaelson et al., 1996). Given these estimates, and considering the sensitivity of the volume of thawed soil to surface characteristics and underlying soil properties, the ability to represent variations of active-layer thickness accurately over large areas is crucial to efforts at quantifying the flux of greenhouse gases in tundra environments. Information about the spatial variability of the active layer is also important for hazard mapping and identifying areas where the infrastructure could be threatened by thermokarst (Nelson et al., 1993; Williams, 1995; Anisimov and Nelson, 1996).

Although considerable research has been carried out on permafrost dynamics and permafrost-vegetation relations, little has been done to explicitly describe or map spatial variations of active-layer thickness ("thaw depth") at regional scales. The problem has long been recognized as important, but the high spatial variability of thaw depth and the large effort required to characterize it systematically have precluded the production of detailed regional maps. Maps that portray active-layer thickness have been identified as a priority of arctic climate-change research and are a component of the National Science Foundation-sponsored ARCSS/LAII (Arctic System Science/Land-Atmosphere-Ice Interactions) Flux Study in northern Alaska (Weller et al., 1995). Such maps have potential uses in a broad range of multidisciplinary climate-change research in the Arctic. For example, a map of active-layer depths provides an approximation of the overall volume of thawed soil in a region and could be used with estimates of microbial respiration to help quantify the release of greenhouse gases.

This paper reports our use of geographic information systems (GIS) to produce detailed regional maps of active-layer thickness. The study uses climate data collected at sites distributed over a large area, draws on a database constructed by widespread and intensive sampling of thaw depth, and bases its spatial extrapolations on digital elevation data and land-cover classes derived from Landsat imagery. Given the difficulty of actually sampling active-layer thickness across large areas, measurements from relatively small areas must be "scaled up" to larger ones. The work is part of a larger effort (Weller et al., 1995) to address

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the feasibility of extrapolating plot-level data in arctic ecosystems to watershed and regional scales.

Previous Work

The traditional method of measuring thaw depths by pushing an incremented metal probe into the ground is effective for small areas but impractical over large regions. Although active-layer thickness has not yet been mapped directly through satellite remote sensing, land cover (primarily vegetation) may provide a partial basis for inference (Hall, 1988; Gross et al., 1990; Peddle and Franklin, 1993; Leverington and Duguay, 1996). Active-layer thickness is influenced by many factors in addition to vegetative cover, however, and active-layer/land-cover correlations must first be established by ground-based measurements (Tyrtikov, 1959; Leverington, 1995). Consideration of several other factors that influence active-layer thickness can increase the accuracy of its estimation.

Because the thickness of the active layer is determined in the first instance by regional climate, most analytic treatments have used air temperature measured at nearby point locations as its primary determinant (e.g., McRoberts, 1975). Broad spatial patterns related directly to macroclimate can indeed be discerned at regional and global scales (e.g., Jahn and Walker, 1983; Anisimov et al., 1997), but such procedures involve summarizing or making assumptions about more localized measurements, which may reflect extreme variability. Active-layer thickness can vary substantially over short distances because heat transfer in moist soils subject to freezing and thawing reflects the interaction of a large number of highly localized factors, including vegetation type, snow cover, organic layer thickness, soil thermal properties, soil moisture, microtopography, and the operation of nonconductive heat-transfer processes (Outcalt et al., 1990). Although numerical models of ground thermal evolution have successfully incorporated combinations of these variables at point locations (e.g., Nakano and Brown, 1972; Outcalt, 1976; Goodrich, 1982; Anisimov, 1989; Waelbroeck, 1993), problems involved in characterizing their covariation at high resolutions over large areas can approach intractability. Conversely, drawing regional inferences from detailed measurements made at a very small number of point locations (e.g., Romanovsky and Osterkamp, 1995) raises concerns about the spatial representativeness of the measurement sites.

Several previous studies (Gray et al., 1988; Jorgenson and Kreig, 1988; Kirkby, 1995; Leverington, 1995) relate closely to the problem addressed in this paper. Gray et al. (1988) sampled the active layer repeatedly at level sites in six vegetation/soil categories ("terrain types") in northern Quebec. By correlating these records with thawing degree-day accumulations from two nearby climate stations, Gray et al. (1988) were able to construct relationships between air temperature records and thaw depth for each of the terrain types, which could then be used to make predictive statements about other locations in the study area with similar covers. Topographic effects were not considered explicitly. Jorgenson and Kreig (1988) employed degree-day ratios to map permafrost at the local scale (cf. Nelson, 1986), using equivalent latitude to discern topoclimatic effects within a small area of complex terrain in central Alaska. Because active-layer thickness was a necessary component in Kirkby's (1995) GIS analysis of the impact of climate warming on gelifluction rates in Scandinavia, several raster-based maps of thaw depth were a by-product of the study. Leverington (1995), working in central Yukon, concluded that substantial differences in depth to frozen ground can exist within closely spaced areas, despite similar land-cover characteristics within the units.

The maximum annual thickness of the active layer on Alaska's North Slope is generally less than 1 m (Carter et al., 1987). In other permafrost regions this value is usually between 15 cm and several meters, with deeper thaw occurring mainly near large water bodies (Washburn, 1980: 57). Precise characterization of the great local variability in active-layer thickness demands application of hierarchical sampling methods and formal statistical characterization, but only a few examples of such work are available for Alaska (Nelson and Outcalt, 1982; Fagan, 1995; Mueller, 1996). These studies indicate that regional patterns can be inferred by working with average values from a series of intensive measurements within representative and well-distributed subunits.

Study Area

The Kuparuk River drainage basin occupies 9201 km^2 in north-central Alaska (Fig. 1c). Its narrow, north-south alignment approximates a transect from the Arctic Ocean near Prudhoe Bay to the Brooks Range. The 26,278-km^2 map area is dominated by several north-flowing rivers, including the Kuparuk, the Sagavanirktok, and the Colville (Fig. 1a). Of these, the entire drainage area of only one, the Kuparuk, is contained in the map area. Much of the Kuparuk region is overlain by loess deposits of varying thickness (Carter, 1981; Kreig and Reger, 1982). The base-rich deposits of the coastal plain and lower parts of the foothills have high pH ($>$6.0) compared to the older surfaces at higher elevations (pH $<$4.5). This difference in pH has a strong influence over the regional vegetation patterns and, through these, affects thaw depth (Walker and Everett, 1991; Walker et al., 1994, 1997). The soils of the Kuparuk basin are varied, but correlate well with the vegetation categories of Figure 1b and Table 1. Moist tundra sites contain highly cryoturbated soils, including Aquaturbels and Histoturbels, the latter in nonacidic localities. Wet tundra on the coastal plain overlies mineral soil with minimal cryoturbation, including Aquahaplels, Histohaplels, and highly decomposed organic soils (Hemistels and Sapristels). Permafrost underlies virtually all of the study area, with the exception of deep thaw lakes that do not freeze to the bottom in winter.

The study area encompasses three of Wahrhaftig's (1965) physiographic divisions of Alaska (Fig. 1a). The southernmost part lies in the Central and Eastern Brooks Range province, an area of rugged, glacially dissected sedimentary rocks. Elevation ranges from 1070 m to local maxima of about 2300 m. Small cirque glaciers are common in this part of the Brooks Range (Ellis and Calkin, 1979). The surficial geology of the mountains includes bedrock and recent glacial deposits (Calkin, 1988). Vegetation is sparse or absent except in river valleys, where riparian shrub communities dominated by willows follow stream courses and moist sedge, dwarf-shrub communities occupy areas of fine-grained soils (Spetzman, 1959; Batten, 1977).

The central part of the map area lies in the Arctic Foothills province, including parts of both its northern and southern subdivisions. Elevation ranges from 180 m in the north to 1070 m in the southern portion of the province. Local topography contains broad east-west trending linear ridges and isolated flat-topped mountains, interspersed with broad river valleys and relatively flat plains. The Arctic Foothills are dominated by glacial deposits, loess, and alluvial sediments (Carter, 1981; Hamilton, 1986, 1994). Vegetation on recent glacial deposits, recent alluvium, and loess areas of the coastal plain and northern foothills

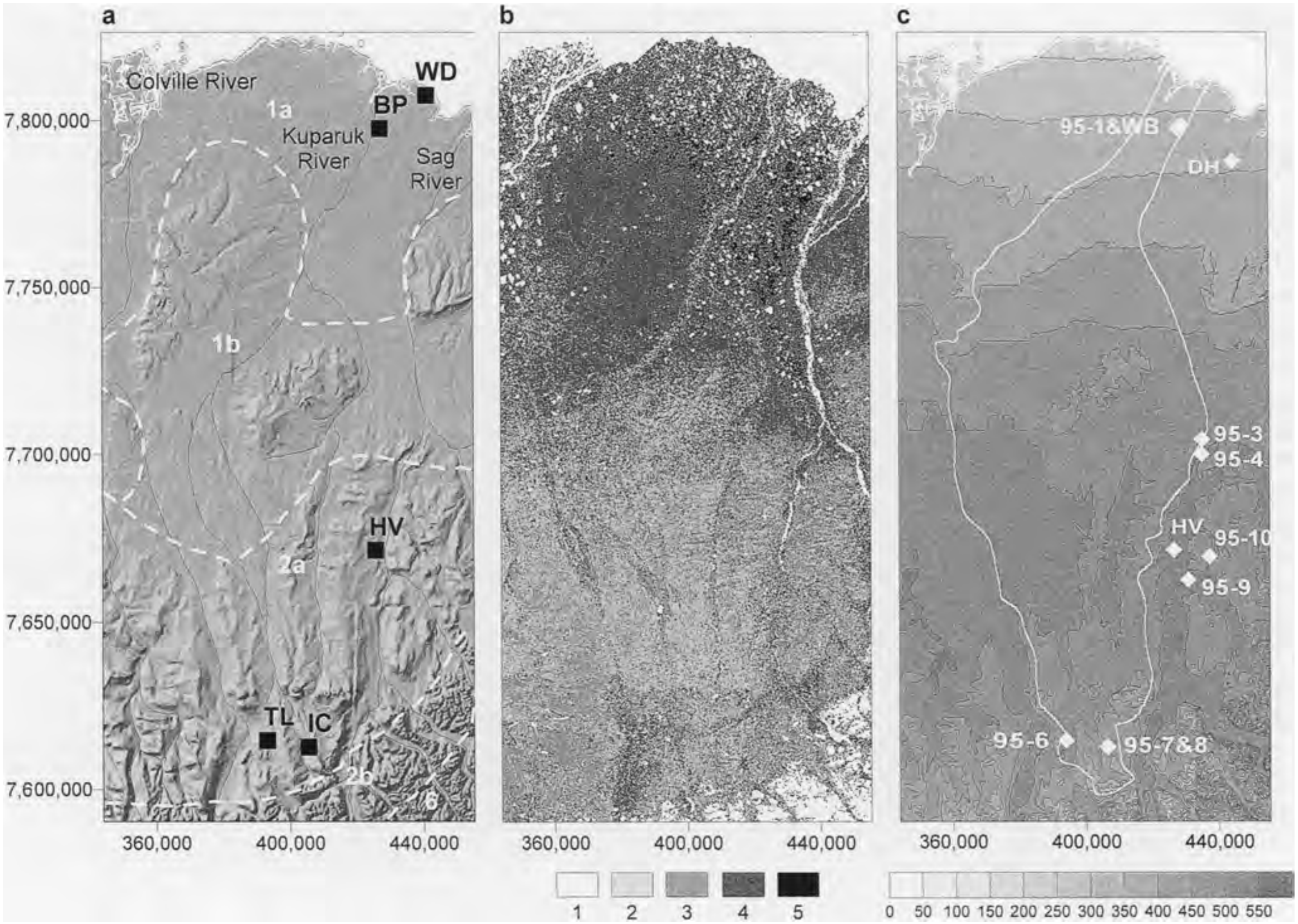

FIGURE 1. (a) Shaded relief map of study area, based on 787 × 371 digital elevation model (300 m node spacing). Locations of ARCSS grids are shown by squares. BP = Betty Pingo; WD = West Dock; HV = Happy Valley; IC = Imnavait Creek; TL = Toolik Lake. Numbers along bottom and left margin are Universal Transverse Mercator (UTM) coordinates, Zone 6, expressed in meters. Generalized physiographic provinces (dashed white lines) are indicated, after Wahrhaftig (1965). 1: Arctic Coastal Plain Province: 1a: Teshekpuk Lake section; 1b: White Hills section. 2: Arctic Foothills Province: 2a: northern section; 2b: southern section. 6: Central and Eastern Brooks Range Province. (b) Land-cover map prepared from Landsat imagery (Auerbach et al., 1996). The version used in this study and shown here is a "thinned" version, in which only elements corresponding to positions of DEM nodes were employed. Land-cover categories denoted by numbers in legend are identified in Table 1. (c) Degree-day field for 11 August ("end-of-season"), obtained using the statistical relation of Figure 3 and environmental lapse rate to adjust values for nodes on the DEM. Labeled symbols indicate locations of Flux Study plots and sites where supplementary data were collected. Flux Study Plots (numbered sites) are described in Table 1. WB = Wet Betty Pingo, DH = Deadhorse, HV = Happy Valley. Kuparuk River basin is delimited by solid line.

contrasts sharply with that on older acidic surfaces (Walker et al., 1994, 1997). The older upland surfaces are dominated by tussock tundra with tussock cottongrass, a suite of acidiphilous shrubs and mosses, and extensive water tracks with shrubby communities. The younger nonacidic surfaces have basiphilous communities composed of sedges, dwarf shrubs, forbs, and mosses.

The northernmost portion of the study area contains parts of both the Teshekpuk and White Hills sections of the Arctic Coastal Plain province. Most of the former is poorly drained. The White Hills section contains localized uplands that accentuate the otherwise gentle rise from sea level to about 180 m near the southern boundary of the province. The coastal plain contains wet tundra and numerous oriented thaw lakes overlying alluvial and lacustrine deposits of Quaternary age (Everett and Parkinson, 1977; Walker et al., 1980, Carter et al., 1987; Walker and Everett, 1991). Deposits of Tertiary gravels are exposed locally in the White Hills section. Ice-wedge polygons underlie much of the province, and the landscape is marked by distinctive, repeating patterns of different vegetation types in the microhabitats of polygon rims, centers, and troughs. The predominant vegetation in wet areas is composed of sedges. Moist areas have tundra similar to the vegetation of the upland areas of the Foothills. River courses in warmer areas of the foothills and coastal plain contain alder, as well as the willows found farther south. The digital land-cover map of the area (Fig. 1b, Table 1), used analytically in this study, is based on Landsat Multispectral Scanner imagery (Auerbach et al., 1996).

Long-term climatic observations within the region have been conducted by the U.S. Army Cold Regions Research and Engineering Laboratory (Berg et al., 1978; Haugen and Brown, 1980; Haugen, 1982) and reflect a climate with very cold winters

TABLE 1

Landcover classes[a] (vegetation/soil associations) and corresponding Flux Study plots used to develop thaw-depth/degree-day relations (Figs. 1c, 3, and 4)

1) *Barrens*: barren, lichen-covered and partially vegetated rocks in the foothills and mountains; barren and partially vegetated alluvium in river bottoms. Soils: Orthohaplels, Haploturbels, Argihaplels, Umbrihaplels. Reference Flux Study plots: Imnavait Mountain and Riparian (neither used in thaw-depth calculations). *Water and shadows*: water bodies, marshes with aquatic vegetation, and shadows, mainly on north-facing slopes in Brooks Range and Arctic Foothills. *Clouds and ice*: aufeis along braided streams and clouds, mainly at high elevations.
2) *Moist acidic tundra*: tussock tundra dominated by sedges with pH < 5.0. Soils: Aquaturbels, Histoturbels, Aquahaplels, Histohaplels. Reference Flux Study plot: Sagwon 1 (95-3).
3) *Shrublands*: riparian shrublands along rivers; watertracks and shrublands in Foothills basins; tussock tundra dominated by shrubs. Soils: Orthohaplels, Aquahaplels, Mollihaplels, Aquaturbels, Histoturbels Histohaplels. Reference Flux Study plot: Happy Valley Water Track (95-10).
4) *Moist nonacidic tundra*: found on hillslopes and moderately well-drained surfaces with pH ≥ 5.0. Soils: Histoturbels, Histohaplels, Aquaturbels, Aquahaplels, Hemistels, Sapristels. Reference Flux Study plots: Betty Pingo 1 (95-1) for lowland locations (elevations ≤200 m); Sagwon 2 (95-4) for uplands (elevations >200 m).
5) *Wet tundra*: rich fens on coastal plain; along rivers, and in Foothills basins; poor fens in foothills at higher elevations and on older surfaces; complexes of wet and moist tundra on coastal plain in association with ice-wedge polygons. Soils: Aquahaplels, Histohaplels, Hemistels, Sapristels, Fibristels. Reference Flux Study plots: Wet Betty Pingo (NW quadrant of 1 × 1 km ARCSS Betty Pingo grid) for lowland locations (elevations ≤200 m); Toolik Water Track Complex (95-6) for upland locations (elevations >200 m).

[a] Numbers correspond to legend of Figure 1b. Dominant soils are named according to the recently proposed soil order for permafrost-affected soils, the Gelisols (Bockheim et al., 1994; ICOMPAS, 1996). Details about vegetation and soils at individual Flux Study plots are provided in Auerbach and Walker (1995), Auerbach et al. (1996), and Walker and Bockheim (1995).

and cool summers. Winds are a major factor on the Arctic Coastal Plain. During summer, a persistent northeasterly sea breeze develops near the coast in response to temperature contrasts between open water in the Arctic Ocean and warmer tundra inland (Kozo, 1982). A continentality gradient is apparent, with larger diurnal and annual temperature amplitudes in the Arctic Foothills than on the Arctic Coastal Plain. Thawing degree-day sums in the Brooks Range are limited by elevation at many locations. The summer temperature gradient is particularly steep and persistent in a narrow band near the coast (Haugen, 1982, Table 1; Zhang et al., 1996; cf. Burn, 1997), where its alignment corresponds with the local sea breeze (Haugen and Brown, 1980; Haugen, 1982). Except in the higher elevations of the Brooks Range, annual precipitation throughout the study area is low (140–267 mm). Compared to the Arctic Foothills, a larger proportion of the precipitation falls as snow in the Arctic Coastal Plain.

Methodology

LOCATIONS

Fieldwork was conducted from mid-June through early September 1995, at a series of sites ("Flux Study plots") on a transect between Prudhoe Bay and Toolik Lake. Locations were chosen by Flux Study investigators to be representative of the primary land-cover (vegetation/soil) associations in the central part of Alaska's North Slope. At each site data were collected within a surveyed and georeferenced 1-ha plot. Locations are shown and described in Figure 1c and Table 1, respectively. The numerical sequence used to identify these plots is employed by all Flux Study subprojects.

Supplementary thaw-depth data were collected on three dates at regularly spaced intervals on 1 × 1 km "ARCSS Grids," located near West Dock, Imnavait Creek, Toolik Lake, and Happy Valley (Fig. 1a). Each grid consists of 121 permanent stakes, precisely located at 100-m intervals. Together, the grids provide a good representation of the climatic and topographic diversity within the Kuparuk River basin. Thaw-depth measurements made on these grids were used to verify the active-layer map, but were not used in its construction.

FIELD PROCEDURES

Each of the Flux Study plots was instrumented with 10 miniature thermal data loggers[1]. Two supplementary sites at Deadhorse and Happy Valley were also instrumented (Fig. 1c). At each site, one sensor was placed in a radiation shield and mounted atop a stable mast. Nine loggers were placed in various microtopographic positions within the plot at the vegetation/soil interface. All loggers were set to read simultaneously at 15-min intervals, and the entire network was operational on 23 June 1995. Readings continued until mid-August, when the loggers were downloaded and reset to record at hourly intervals for the 1995-96 winter. This paper reports results obtained with the thermal records for the period 23 June through 11 August 1995, with emphasis on the air temperature records. The strategy reported here uses these partial seasonal records to construct a statistical relation between degree days and active-layer thickness.

The active layer was probed within the Flux Study plots on at least three occasions during the period of study. Procedures involved pushing a rigid metal rod, calibrated in centimeters, through the active layer to the point of refusal, interpreted in most cases to be the frost table (the upper layer of ice-bonded soil). Mackay (1977, 1995) discussed some potential sources of error associated with this methodology; a thermal probe similar to that employed by Mackay (1977) has been used extensively at several times and locations in our work on the North Slope to verify that the depth at which mechanical resistance was encountered coincided with the position of the 0°C isotherm. Some locations in the southern part of the study area contained clast-rich glacial till, and extra care was taken when probing to distinguish between rock fragments and the frost table.

Thaw-depth samples (71 individual readings per plot per sampling date) at each Flux Study location were obtained by probing at 5-m intervals along the plot's two perpendiculars and a third, diagonal transect. Comparison of results from this procedure with an exhaustive determination of thaw depth in five of the plots showed it to be an effective sampling design (Fig. 2).

[1] StowAway™ 8 kb thermal loggers equipped with external thermistors, manufactured by Onset Computer Corporation, Pocasset, MA, U.S.A. These units have an effective temperature range of −50°C to +33°C, with resolution of approximately 0.3°C. Each logger is capable of making and storing approximately 8000 measurements, which translates into hourly measurements for 331 d, or a 15-min interval for 82 d.

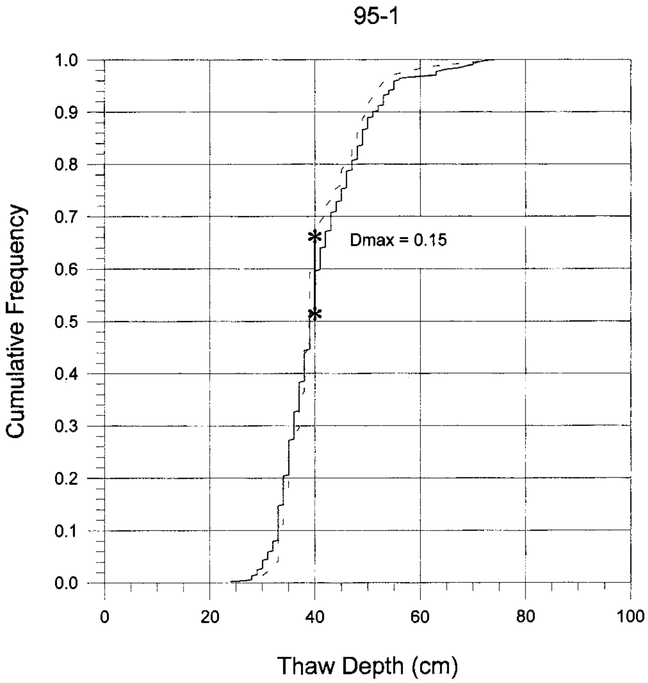

FIGURE 2. Comparison of results from 71-point sampling design (dashed line) with a more intensive 441-point probing effort (solid line) at the 95-1 Flux Study plot. D_{max} is the maximum difference, represented by stars, between the two cumulative frequency distributions, and forms the basis for the Kolmogorov-Smirnov goodness-of-fit test (e.g., Gibbons 1976: 56–75). No significant differences (P = 0.1) were found between the sample and "population" distributions at any of the five plots examined using this strategy.

THAW-DEPTH CALCULATIONS

The literature describes many analytic and numerical methods for predicting the depths of freezing and thawing in soils (see, for example, summaries contained in Jumikis, 1977; Lunardini, 1981; Andersland and Ladanyi, 1994). Most require substantial site-specific input parameters, however, and this requirement has hindered development of methodologies for addressing active-layer thickness over large areas. A feature common to many of the analytic treatments is that thawing (and freezing) depths are proportional to the square root of time.

The Stefan solution provides a useful method for predicting the depth of thawing (Z_{al}) in soils when little site-specific information is available. A basic version of the Stefan solution has the form

$$Z_{al} = [(2\, n\, \lambda t\bar{T})/(\rho w L)]^{1/2} \tag{1}$$

where n is the dimensionless ratio of seasonal ground-surface and air temperatures, known as the "n-factor" (Shur and Slavin-Borovskiy, 1993), λ is the thermal conductivity of thawed soil (W m^{-1} °C^{-1}), t is the duration of the warm ($\geq$0°C) season (s), $\bar{T}$ is mean temperature during the warm season (°C), ρ is soil density (kg m^{-3}), w is relative water content expressed as a decimal proportion, and L is the latent heat of fusion (J kg^{-1}). The quantity $t \cdot \bar{T}/86{,}400$ defines the "thawing index" DDT (°C d), a time-temperature integral usually calculated by summing mean daily temperatures above 0°C.

The Stefan solution can be expressed as

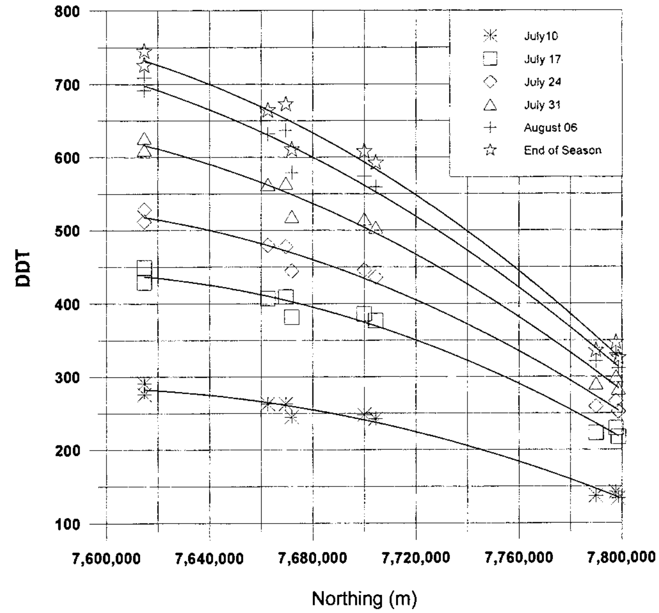

FIGURE 3. Relation between distance from Arctic Ocean (expressed as UTM northings, in meters) and thawing degree day sums (adjusted to sea level using a lapse rate of 0.64 °C/100 m) at weekly intervals for the Flux study sites. Degree-day figures are totals for the period 23 June to 11 August. Coefficient of determination for second-degree polynomial regression equations is at least 0.98 in all cases.

$$Z_{al} = bt^{1/2} \tag{2}$$

where b is a variable with dimensions m s$^{-1/2}$, representing the other parameters from equation (1). Equation (2) has been used in many studies (e.g., McRoberts, 1975; Jahn and Walker, 1983; Mackay, 1995) to calculate active-layer thickness, and has proven to be a reasonable approximation in situations where some data are available to characterize soil properties and local climate.

Hinkel and Nicholas (1995) employed a variant of (2) to describe the seasonal progression of active-layer thickness at a location in central Alaska. The form of the Stefan relation used by Hinkel and Nicholas is

$$Z_{al} = \beta\, DDT^{1/2} + a, \tag{3}$$

a simple regression-type equation in which β describes the rate of thaw progression. The parameter a is simply an intercept, necessary in the present study because there is no temperature record for the early part of the thaw season.

ANALYSIS

The air temperature records obtained at the Kuparuk sites in Figure 1c were reduced to sea level using an environmental lapse rate of 0.64°C/100 m and transformed by summation of mean daily temperature into thawing degree-day totals for the period of record, 23 June through 11 August 1995. Figure 3 shows relations between latitude and degree-day accumulations at weekly intervals over the Kuparuk transect. A second-degree polynomial expression, developed after reducing the temperature data to sea level, accounts for more than 98% of the variation in the data set for each of six dates, demonstrating a relatively simple relation between geographic position (elevation and distance from the Arctic Ocean) and summer air temperature within the study area. This relation was employed to construct degree-day fields for the en-

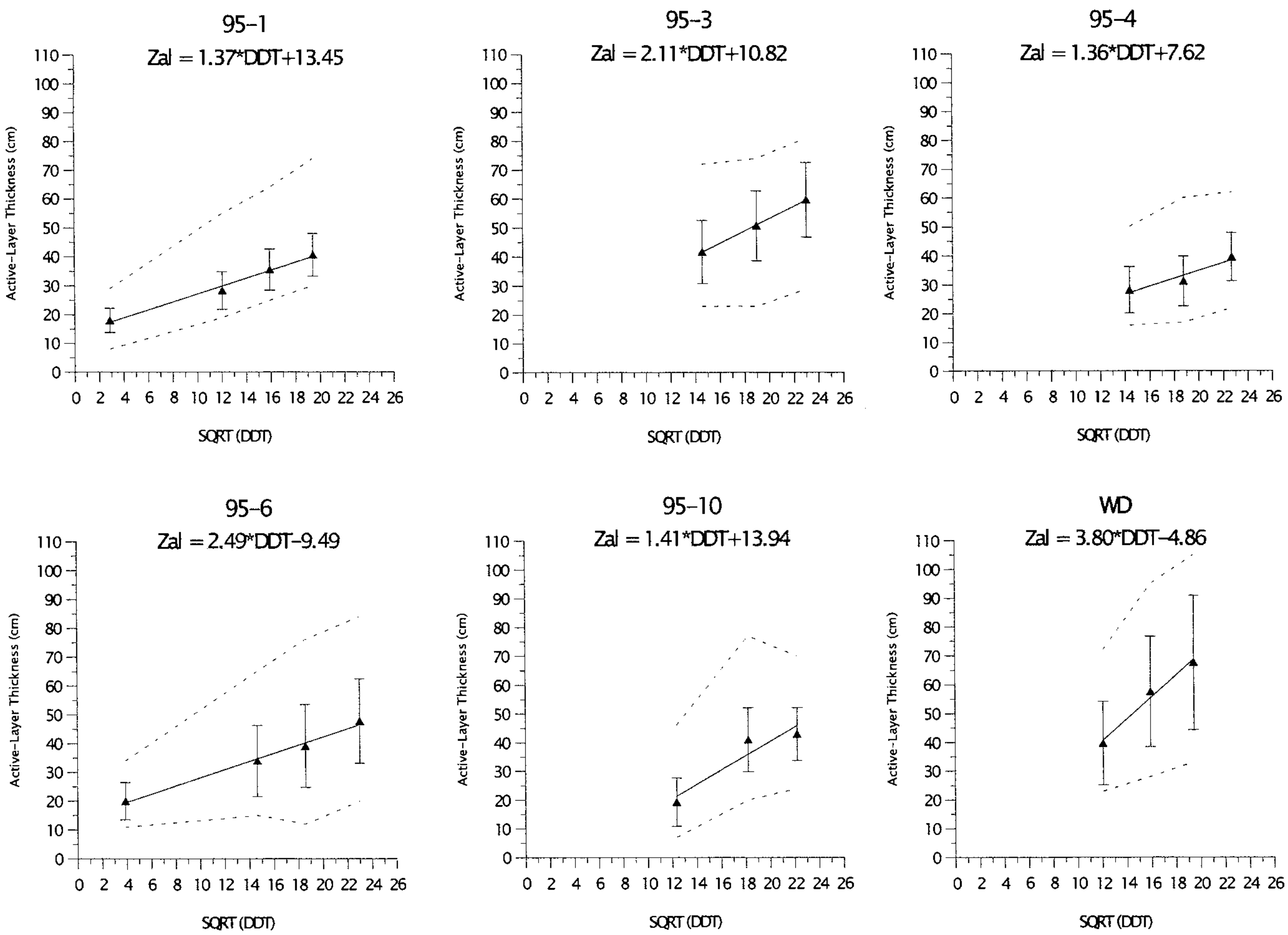

FIGURE 4. Statistical relation between mean thaw depth (71 replications per plot per date) and accumulated degree days (mast level) at individual Flux Study plots. Filled symbols represent mean thaw depth on specific probing dates, bars indicate standard deviations, and dashed lines show range (minimum and maximum) of values. Equations, represented by solid lines, represents the Stefan relation for each of the Flux Study plots, in the form given by equation (3).

tire map area (Fig. 1c) by using the polynomials and the environmental lapse rate specified above to calculate a degree-day value for each node on a digital elevation model (DEM) of the study area (Fig. 1a).

A linear relation (equation 3) was developed between mean thaw depth and degree-day accumulation for each of the Flux Study plots, a procedure similar to that employed by Gray et al. (1988) in northern Quebec. These relations are shown for the Flux Study plots in Figure 4; the general Stefan relation between thaw depth and the square root of thawing degree days applies at each of the locations. The value of β (thaw rate) is highly variable between sites owing to differences in surface cover, soil thermal properties, and soil moisture.

Despite the straightforward relations between active-layer thickness, interpolated degree-day sums, and land-cover category demonstrated by these data, it is important to recognize that they were collected from flat-lying surfaces and that topoclimatic effects complicate efforts to extrapolate them to all DEM nodes in the basin. Differential receipts of solar energy on slopes of varying orientation and gradient can lead to substantial, systematic differences in thaw depth (e.g., Nelson and Outcalt, 1982; Nelson and Spies, 1991), although other factors have been known to complicate the relation between radiation receipt and the depth of thaw (e.g., Price, 1971; Hannell, 1973).

To address topoclimatic effects, potential global solar radiation was calculated for each DEM node using Swift's (1976) algorithm. A procedure developed by Nelson and Spies (1991) was used to construct, for each DEM node, a topoclimatic index given by

$$r = R_s/R_h \quad (4)$$

where r is a dimensionless parameter analogous to the n-factor, R_s is potential global radiation incident on a sloping surface of specified latitude, gradient, and orientation, and R_h is potential global radiation on a horizontal surface at the same geographic location. Daily values of R_s and R_h were integrated numerically from 1 June until the appropriate dates to construct the maps described in the next section. Active-layer thickness within each DEM element was calculated as

$$Z_{al} = \beta_v[rDDT]^{1/2} + a_v \quad (5)$$

where β_v and a_v are regression coefficients derived empirically from the Flux Study plots (Fig. 4), and applied as appropriate for the land-cover class at individual DEM nodes. The value attached to each node represents an average for the 300 × 300 m area. The land-cover class for each node was obtained from the digital land-cover map (Fig. 1b) and corresponds to the classes detailed in Table 1. A more complete description of the topoclimatic adjustments is provided in Nelson et al. (1997).

By necessity, "end of season" was taken as 11 August, the last day before seasonal downloading on which all temperature loggers were operating simultaneously. Because thaw progression is proportional to the square root of time and there were no unusually warm periods recorded elsewhere on the North Slope in late August, there are likely to be only small differences between the depth of thaw on this date and in early September, when several sites were checked.

Results

Figure 5 illustrates thaw progression at weekly intervals over the period of study, based on equation (5). The high degree of complexity evident in these maps increases as the thaw season progresses, and is consistent with field evidence from the Flux Study plots and the ARCSS grids. The maps contain both a regional signal, attributable to climatic gradients, and local variability arising from various combinations of vegetation/soil associations, soil moisture and thermal properties, and the effects of complex terrain. The 11 August map (Fig. 6a) shows substantial differences in thaw depth over short distances. Clear correspondences can be discerned between local patterns on the topographic (Fig. 1a), land-cover (Fig. 1b), degree-day (Fig. 1c), and active-layer (Fig. 5) maps. The volume of thawed soil associated with wet tundra is disproportionately large, compared to the relative areal extent of this land-cover category (Table 2). Conversely, the volume of thawed soil associated with the moist acidic tundra category is proportionally smaller than its areal extent.

REGIONAL PATTERN

Because they are less continental, coastal locations show smaller degree-day accumulations than do inland sites. The sequence shown in Figure 5 depicts the active layer thickening from south to north, a response initially to the timing of snowmelt and thereafter to the seasonal progression of regional temperature. Comparison of subareas of the maps in Figure 5 with the trends shown on Figures 1c and 3 confirms the primacy of degree-day accumulation as an explanation for the regional trend of thaw depth. The spatial manifestation of the effects of degree-day accumulation on active-layer development is best illustrated on the coastal plain (north of UTM 7,725,000 N), by the northward expansion of the light-toned 40–45 cm thaw-depth class on panels c–f of Figure 5. The gentle topography and relatively homogeneous land cover in this part of the map area (Figs. 1a, 1b) result in a simple pattern that cartographically isolates the effects of temperature throughout much of the northern part of the map area. Conversely, large areas occupying the higher elevations of the Arctic Foothills (south-central part of the map) show very slow thaw progression. This situation is a response to small degree-day accumulations and a thick insulating cover of organic material provided by the moist acidic tundra category occupying most upland surfaces.

LOCAL VARIATION

The general regional pattern outlined above is punctuated by accelerated thaw progression occurring adjacent to water bodies on the Coastal Plain, along major river valleys, and on certain upland land-cover types. Topoclimate is also responsible for substantial contrasts in thaw depth over short horizontal distances.

Arctic Coastal Plain

Extreme spatial variability occurs in the outer reaches of the coastal plain. Intensive probing on the ARCSS 1 × 1 km grids at Betty Pingo, West Dock, and outside the study area at Barrow demonstrated that depressions formed by drainage of shallow lakes often have thaw depths more than twice as great as those in immediately adjacent uplands (Hinkel et al., 1997). Because these differences often occur over horizontal distances of 20 m or less, the raster representation of Figure 5 provides effective visualization of actual field conditions. Figure 4 shows the difference in thaw rate at the two immediately adjacent Betty Pingo sites (95-1 and WB). The lower albedo, the reserve of heat provided by standing water, and the relatively high thermal conductivity of saturated soils at the wet site leads to a rate of thaw much greater than at Site 95-1, where soils are characterized only as moist.

River Valleys

Although the thaw-depth map for early July (Fig. 5a) gives the impression of relative homogeneity, by the middle of the month (Fig. 5b) distinctive linear zones of advanced thaw develop in proximity to major streams. This pattern persists and intensifies throughout the thaw season. The lower elevations along these mature stream valleys lead to larger degree-day accumulations, and the thermal properties of the wet tundra soils enable rapid thaw penetration. The largest computed thaw depths in the entire map area occur along the courses of the Sagavanirktok and Kuparuk Rivers between Prudhoe Bay/Deadhorse and the northern extremities of the Arctic Foothills.

Upland Associations

One of the more striking findings of the Flux Study is the sharp ecological contrast between acidic and nonacidic tundra in the northern part of the Arctic Foothills (Walker et al., 1997; Bockheim et al., 1998). The nonacidic tundra is developed on calcareous loess of recent origin derived from the Sagavanirktok River (Walker and Everett, 1991), and has a thinner organic layer than adjacent patches of acidic tundra. The contrast in active-layer thickness between these two units is illustrated by sites 95-3 and 95-4; the nonacidic tundra site experiences an end-of-season mean thaw depth 50% greater than that on the acidic tundra, despite the proximity of the sites. Other vegetative and edaphic contrasts between the acidic and nonacidic categories are detailed by Walker et al. (1997). Owing to the complex interfingering between these categories in the the Arctic Foothills province, thaw depth forms a very complex mosaic in this part of the map, with adjacent pixels showing differences of 20 cm or more (Fig. 6a). The close correspondence between the 200 m contour and some areas with relatively great active-layer thickness in the northern foothills reflects use of this elevation as a "switch" between the equations for upland and lowland moist nonacidic tundra (see Table 1, Fig. 4).

Topoclimate

The effects of topoclimate, although more subtle, contribute an important dimension to the active-layer maps. These effects were isolated by constructing a digital active-layer map, identical to Figure 5f in all respects except that the topoclimate index (equation 4) was not used in its construction. This matrix was then subtracted from the one on which Figure 5f is based. Figure 6b, the cartographic representation of this operation, indicates that topoclimate may account for differences in mean thaw depth of more than 10 cm. Further details are given in Nelson et al. (1997).

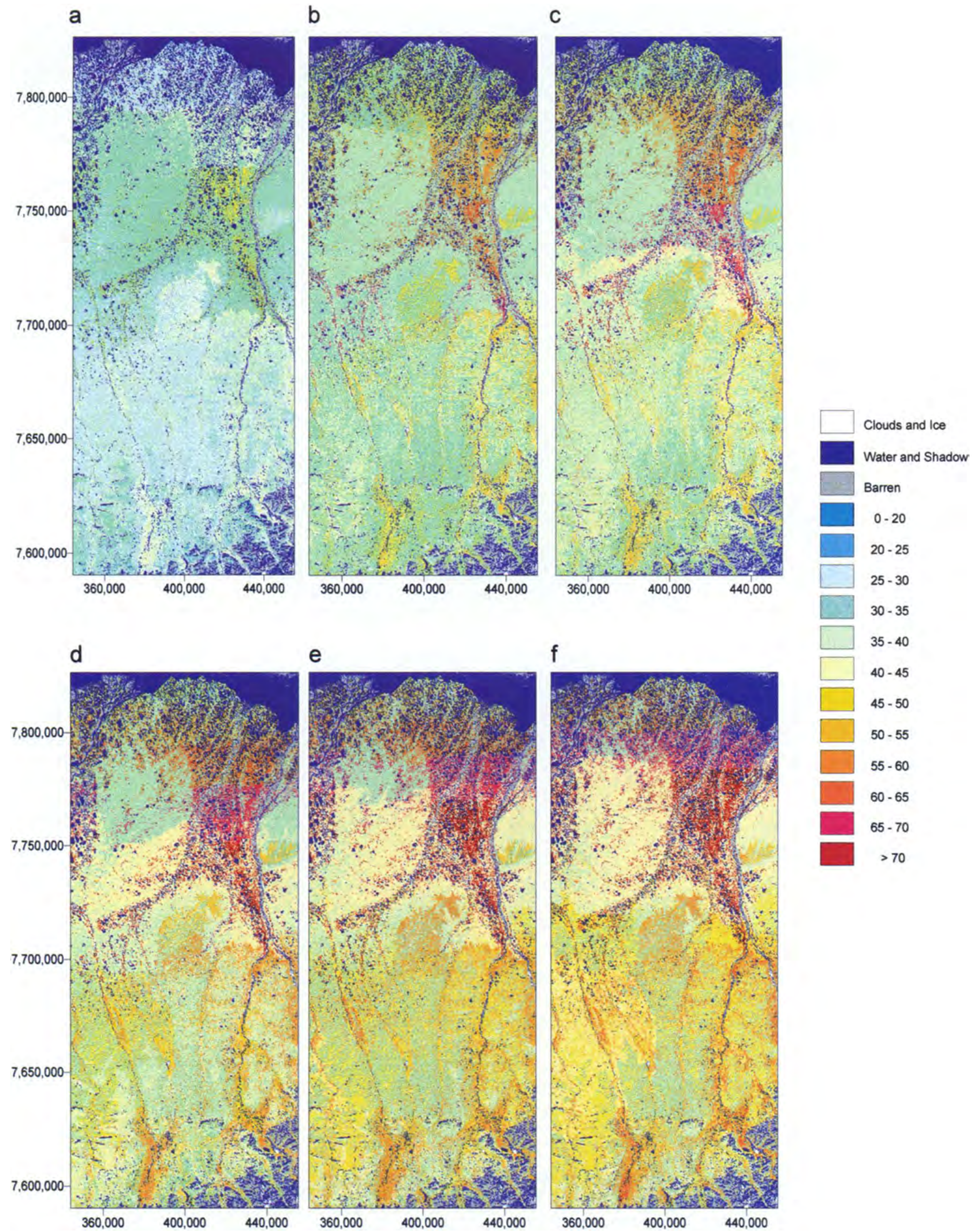

FIGURE 5. Active-layer thickness maps. These maps represent an integrated response to elevation-adjusted thawing degree-day totals, vegetation, moisture, and soils, through use of a regression equation for each land-cover type, and a topoclimatic index. (a) 10 July, (b) 17 July, (c) 24 July, (d) 31 July, (e) 06 August, (f) 11 August ("end of season"). Numbers along bottom and left margins are UTM coordinates (m), Zone 6. Legend given in cm.

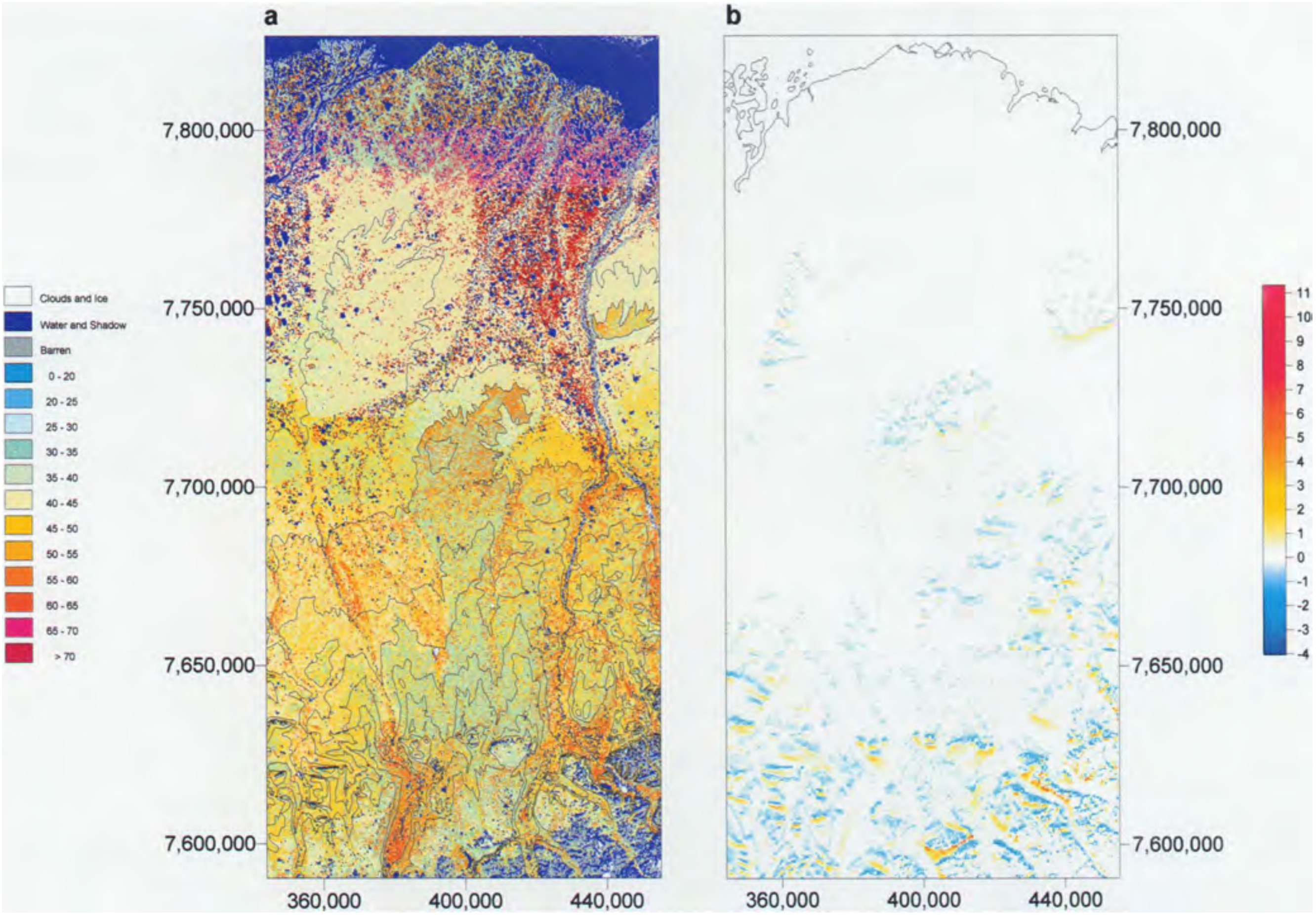

FIGURE 6. (a) Map for 11 August (Fig. 5f), showing relation between active-layer thickness and topography. Contour interval is 100 m, legend for active layer given in cm. Owing to complexity of terrain in Brooks Range (extreme southern part of study area), maximum contour shown is 800 m. (b) Difference map, depicting topoclimatic effects. Active layer is thinner (negative values; blue shading) on cooler, north-facing slopes and thicker on warmer, south facing slopes (positive values; yellow to red shading).

VALIDATION

Thaw-depth data were collected on three occasions at each stake on the West Dock, Happy Valley, Toolik Lake, and Imnavait Creek 1 × 1 km ARCSS grids. Observed and predicted values are in close correspondence (Fig. 7); differences range from 0 to 6.1 cm, with the average error less than 10% of the observed value. The computed value of Willmott's (1981) "index of agreement" is 0.91, indicating a high degree of predictive power. The index of agreement is a dimensionless parameter ranging between zero and unity, but avoids problems often encountered with regression-based goodness-of-fit techniques.

TABLE 2

Relationships between area occupied by each land-cover category and calculated volume of underlying thawed soil[a]

Landcover class	Kuparuk Basin Area ($m^2 \times 10^9$)	Kuparuk Basin Volume ($m^3 \times 10^9$)	Mapped Area Area ($m^2 \times 10^9$)	Mapped Area Volume ($m^3 \times 10^9$)
Moist nonacidic	3.63 (41.7)	1.66 (42.7)	8.73 (40.0)	3.98 (39.8)
Moist acidic	2.85 (32.7)	1.05 (27.0)	6.15 (28.2)	2.37 (23.7)
Wet tundra	0.65 (7.5)	0.46 (11.8)	2.30 (10.5)	1.52 (15.2)
Shrublands	1.57 (18.0)	0.72 (18.5)	4.66 (21.3)	2.14 (21.4)

[a] Numbers in parentheses indicate percentage of total vegetated land area occupied by particular classes. Barren, water and shadows, and clouds and ice categories were not considered in calculations.

Conclusions

The work reported here demonstrates that it is feasible to map active-layer thickness over extensive areas. The close correspondence between observed and predicted values indicates that, if compiled and averaged over a series of years (e.g., one decade or more), maps such as Figures 5 and 6 could be useful as baseline documents for comparison with modeled results in climate-change studies (Anisimov et al., 1997).

Active-layer monitoring will also be an important component of observational programs focused on detecting the effects of global change in the high latitudes (Goodison and Nelson, 1997). Several of the Kuparuk sites are part of the Circumpolar Active Layer Monitoring (CALM) program (Brown, 1996; Brown et al., 1997). Long-term monitoring of the active layer will help to discern complex interrelations between, for example, warmer surface temperatures and the thermal insulation provided by increased plant growth (Myneni et al., 1997).

Continued environmental monitoring and sampling in the Kuparuk basin, tied closely to an expanded validation effort, are being used to put subsequent mapping experiments on a fully

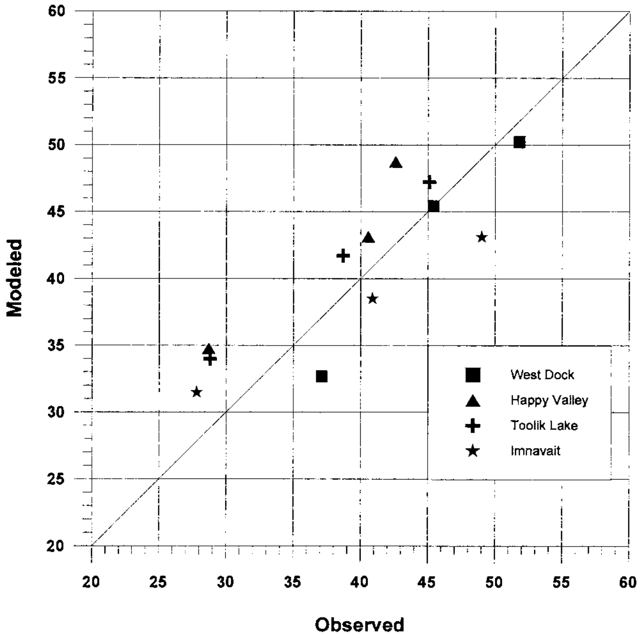

FIGURE 7. Results from accuracy assessment. Predicted mean values for the four 1 × 1 km ARCSS grids in and near the Kuparuk River basin are in close agreement (≤6.1 cm) with those measured at the grids.

deterministic basis. Used in conjunction with satellite remote-sensing data and results from climate models, the approach outlined in this paper holds potential for research into the interactions between permafrost and climate over even larger areas.

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