

Statistical representation of landscape-specific active-layer variability

N.I. Shiklomanov & F.E. Nelson

Department of Geography and Center for Climatic Research, University of Delaware, Newark, DE, USA

ABSTRACT: A major difficulty in predicting and mapping active-layer thickness stems from its large spatial variability over a wide range of geographic scale, in response to many interacting climatic and terrestrial factors. This paper addresses the problem of spatial and temporal variability of active-layer thickness over a wide range of scales, and the landscape-specific effects of this variability in several contemporary environmental settings. Data from long-term, spatially oriented field investigations are used in this study to examine regularities in the active layer for several landscape types. Statistical representations of the thaw depth variability, for each generalized landscape type characteristic of the continuous permafrost zone in northern Alaska, are adopted to summarize the results. Such representations can facilitate a more detailed evaluation of currently available small-scale permafrost models, provide a basis for model downscaling, and bridge a critical gap between small-scale models of climate-permafrost interactions and localized thaw depth measurements.

1 INTRODUCTION

Because most biological and hydrological activities in arctic soils are confined to the layer of seasonal freezing and thawing, analysis of spatial and temporal variations of the active layer at small geographic scales are required to refine predictions of the response of cold region environments to climatic change. Characterization of the upper layer of permafrost over large areas and its response to global warming have been identified as important priorities in the Arctic climate-change research agenda (Burgess et al. 2000). The major difficulties in describing thaw depth are associated with its pronounced spatial heterogeneity within a wide and nearly continuous range of scale, from less than a meter to hundreds of kilometers. This variation occurs as a combined response to a number of interacting climatic and edaphic (i.e., vegetation and subsurface) factors that influence the thickness of the seasonally frozen and thawed layer. However, currently available techniques for spatial permafrost characterization (Anisimov et al. 1997; Malevsky-Malevich et al. 2001) rely on regular grids with cell sizes of 0.5 degree of latitude/longitude or more and an implicit assumption of homogeneity of all geosystem components within each grid cell. Such dramatic differences between the level of spatial detail provided by currently available spatial active layer models and the level of natural variability reflect the lack of adequate empirical information required for explicit, deterministic evaluation of active layer thickness at finer scales.

Methods of statistical downscaling can be adopted to fill the critical gap between small-scale models and localized thaw depth variability. Such an approach involves developing a probabilistic model that considers the statistical properties of active-layer thickness and other environmental parameters within representative,

easily identifiable landscape units, while accounting for differences between units deterministically by means of models of permafrost-climate interactions (Anisimov et al. 2002). The statistical properties required for probabilistic models include a probability density function to represent the range and statistical distribution of thaw depth outcomes possible for certain environmental conditions, and/or a spatial dependency model (variogram), which can provide insight into the scale and magnitude of the spatial variability of the active layer. Both functions are derived from statistical analysis of field data.

The problem of temporal and spatial thaw depth variability has been addressed in several studies conducted in north-central Alaska (Nelson et al. 1998, 1999; Affleck & Shoop, 2001; Gomersall & Hinkel, 2001; Hinkel & Nelson, 2002). The major findings from these investigations indicate that: (1) the presence of landform elements showing spatial regularity at the landscape scale results in landscape-specific active-layer patterns that repeat on an interannual basis, regardless of absolute value; and (2) the scales of spatial variations within broad landscape categories can be fundamentally different. In this study, we attempt to summarize these findings in statistical active layer representation in a context applicable to probabilistic modeling.

2 STUDY AREA AND FIELD PROCEDURES

Detailed field investigations were conducted in the Arctic Coastal Plain and Arctic Foothills physiographic provinces of northern Alaska (Wahrhaftig, 1965). The sampling strategies were developed over a wide spectrum of scales, within a series of 1 ha and 1 km² areas well distributed along the dominant

north-south climatic gradient (Nelson et al. 1997). Each site contains a combination of climatic, surface, and subsurface conditions. The smaller units were chosen to represent specific vegetation and soil characteristics appearing on a regional geobotanical map (Auerbach et al. 1996; Muller et al. 1998), while the 1 km² units were selected to be representative of combinations of landscape characteristics (Walker & Bockheim, 1995; Nelson et al. 1997). The geobotanical mapping scheme adopted for ecological investigations in the area used a combination of remote sensing and field reconnaissance information to derive vegetation/soil boundaries, resulting in characterization and portrayal of vegetation and soils on a single land-cover map. This approach allows detailed landscape characterization in a region in which the primary landscape units are identified by the dominant land-cover. A summary of the approach can be found in Everett & Parkinson (1977) and Walker et al. (1980). The resulting map depicts five primary landscape units dominated by: *wet tundra (WET)*, *moist acidic tundra (MAT)*, *moist nonacidic tundra (MNT)*, *shrublands (SHR)*, and *barrens* (Walker et al. 1994). It covers a 26,278 km² rectangular area surrounding the Kuparuk River basin and has 50 m resolution. The four main categories used in the Kuparuk land-cover map, supplemented by a complex mixture of vegetation categories, were used to guide extensive active-layer sampling over a broad range of scales. The sampling strategy was based on the assumption that areas with similar land-cover categories possess similar properties that influence the ground thermal regime.

Seven 1 ha sites were selected to represent relatively homogeneous land-cover categories found in particular physiographic provinces, while two sites represent complexity introduced by shallow drainage channels known as “water tracks,” which are common in the Foothills (McNamara et al. 1999). Beginning in 1995, the 1 ha sites have been probed manually at least once each summer. Thaw depth measurements at each site were obtained by probing at 5 m intervals along the plot’s two perpendicular and one diagonal transect, resulting in 71 points per plot per probing date. Comprehensive thaw depth sampling was performed systematically at 5 m intervals at least once in each plot during the 1995–1997 field seasons.

Periodic thaw depth measurements were also conducted at five surveyed and georeferenced 1 km² grids over the period 1995–2000. Two grids (Betty Pingo and West Dock) are situated on the Arctic Coastal Plain and the remaining three (Happy Valley, Imnavait Creek and Toolik Lake) are in the Arctic Foothills. These “ARCSS grids” were selected to represent more generalized conditions found in each physiographic province.

Coastal Plain sites have generally low relief, thaw lakes and drained or partially drained thaw lake basins,

ice-wedge polygons, and moist to wet acidic tundra. Foothills grids demonstrate more terrain variability than those on the Coastal Plain; their more heterogeneous vegetation patterns are dominated by acidic tundra and shrublands. Water tracks are common at Foothills locations. Detailed descriptions were provided by Nelson et al. (1998; 1999) and Hinkel & Nelson (2002). Each grid consists of a square array of surveyed permanent stakes separated by 100 m, yielding an array of 11 × 11 nodes across each grid. Replicated active layer sampling was conducted by manual probing at each stake, yielding a maximum of 121 data points per grid per probing date.

Air temperature was measured continuously at each 1 ha and 1 km² site over the 1995–2000 period. Details on equipment and procedures used for temperature measurements are provided in Shiklomanov & Nelson (2002).

3 SPATIAL DEPENDENCY

Geostatistical methods were used to estimate differences in correlation distances for thaw depth between the different landscape units and physiographic regions.

A variogram summarizes the relationship between the statistical variance and lag, or separation distance (Isaaks & Srivastava, 1989). Data collected at points close to each other are more likely to have similar values and variation will be relatively small. If spatial correlation exists, an increase in separation distance between sample points will result in an increase in variance until a certain distance is reached, at which the data become spatially “unrelated.” Variograms are constructed by plotting variance as a function of separation distance. At the point an increase in separation distance no longer causes a corresponding increase in variance, the variogram reaches a “sill,” beyond which it is constant. The distance corresponding to the sill is called the range. Within this distance, spatial correlation is apparent. The values of the variogram are dependent on the variance of the data.

To compare the spatial dependency structure for each generalized vegetation type, standardized variograms were estimated by dividing variogram values at each lag by the lag variance (Pannatier, 1996). Standardized variograms constructed using 441 regularly spaced measurements made at the most characteristic 1 ha plots are shown in Figure 1. The separation distance was increased in regular increments equal to the spacing between sample points (5 m). Spherical models were fit to experimental variograms for each site.

The widest range was observed at the moist nonacidic site on the coastal plain (MNT-CP), where a monotonic rise of the variogram indicates substantial spatial

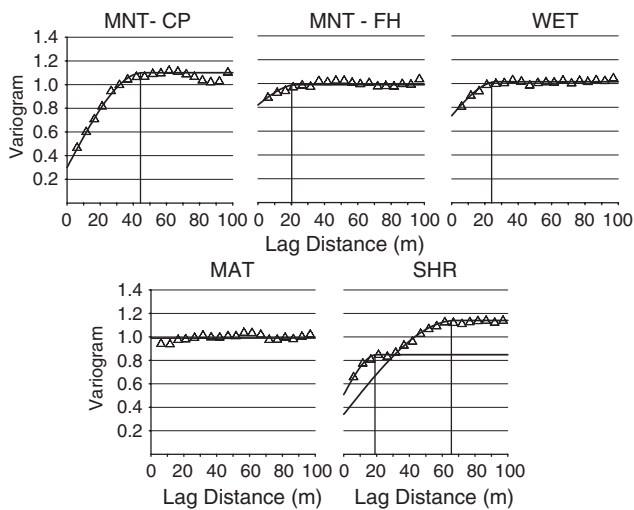


Figure 1. Standardized variograms of active-layer thickness for selected 1 ha sites. Vertical lines represent the “range” of variability.

correlation at distances up to approximately 45 m. At larger separation distances, spatial heterogeneity is introduced by the repeating pattern of the rims, centers, and troughs of ice wedge polygons. In contrast, the moist nonacidic site in the foothills (MNT-FH) shows less pronounced spatial correlation. The sill is reached at shorter separation distances (23 m). The spatial heterogeneity at small distances is attributed to frequent patches of bare ground (frost boils), which are characteristic of non acidic surfaces. At the moist acidic sites (MAT) no significant correlation is found at distances larger than 5 m. The large nugget effect (vertical jump from 0 to variogram value at very short separation distances) indicates that thaw depth values can be very dissimilar at distances less than 5 m.

The primary factors involved are the large micro-topographic differences attributed to tundra tussocks at distances of 1 m or less.

At wet tundra sites in both provinces, observed spatial dependency is similar to variations found in nonacidic sites, with ranges from 20 to 25 m. Nelson et al. (1999) found that in the foothills province 60% of variance is contained in sampling intervals less than three meters. The shrubland site (SHR) shows two distinctive spatial continuity regimes. At small separation distances, active-layer variations are similar to those observed at wet tundra sites. As the distance increases, the second variability regime, attributed to a broader spatial pattern associated with water tracks, becomes apparent.

To provide more insight into the spatial variability of thaw depth at broader scales, variograms of active-layer thickness derived from the 1 km² grids were prepared (Figure 2). Standardized indicator variograms of spatial variation in generalized vegetation classes are superimposed on standardized variograms of thaw

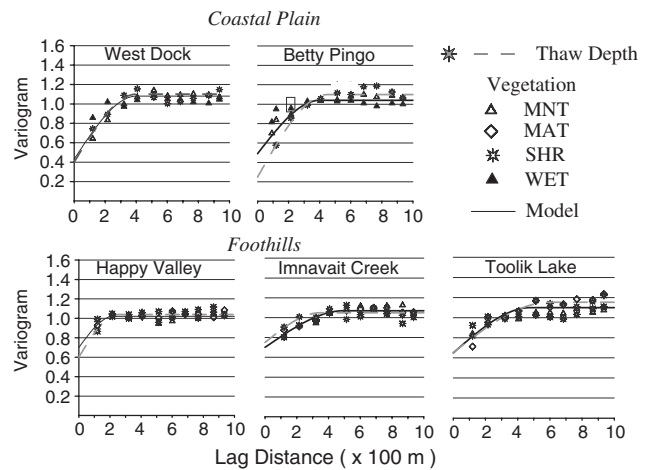


Figure 2. Standardized variograms of vegetation and active-layer thickness for 1 km² grids. One spherical spatial dependency model was fitted visually to four empirical indicator variograms corresponding to vegetation categories at each site.

depth for each site. Landcover categories for each grid were derived from the 50 m resolution landcover map of the Kuparuk region (Auerbach et al. 1996) and resampled to 100 m resolution, consistent with active layer sampling. Indicator transformations were applied to each landcover unit by assigning a value of 1 to the vegetation category of interest and zero to all other categories (Isaaks & Srivastava, 1989).

The indicator variogram, i.e., the variogram for an indicator variable, is often used to reveal the pattern of spatial continuity of nominal ecological variables, such as vegetation type (Rossi et al. 1992). Because indicator variograms of different vegetation classes are similar at all grids, one spherical spatial dependency model was fitted visually to indicator variograms of vegetation categories.

Spatial dependency models of vegetation and active-layer thickness are similar for all sites. At coastal plain locations, low-frequency vegetation patterns with nonacidic tundra are dominant on upland surfaces, while wet tundra predominates in thaw lake basins, resulting in clear continuity in active-layer pattern. The variation range for vegetation and thaw depth is between 300–400 m for both the Betty Pingo and the West Dock grids.

At the Happy Valley site, the diffuse vegetation pattern corresponds to weak spatial dependency of the active layer. A relatively clear continuity in vegetation classes, which can be attributed to topography, is apparent at the Imnavait Creek site. General variations of the active layer are similar to that of vegetation. However, the variogram of thaw depth reaches its sill at a smaller separation distance (300 m vs. 500 m for vegetation). This can be explained by the fact that the Imnavait Creek site is occupied predominantly by acidic surfaces, with large thaw depth variability

occurring at very small separation distances (Figure 1). At the Toolik Lake site, landcover correlates well with topography, resulting in clear spatial continuity of the vegetation pattern.

The variability of the active layer corresponds well to that of the vegetation, with most spatial variation occurring at distances less than 500 m.

Taken as a whole, Figure 2 indicates that at larger distances spatial variation of vegetation composition can be used as a good indicator for that of active-layer thickness.

4 PROBABILITY DENSITY FUNCTIONS

Statistical variability of input parameters reflected by probability density functions (PDF) is a key element of probabilistic models, including those used for statistical downscaling. Large interannual variability of thaw depth as a response to climatic forcing, however, makes it difficult to characterize landscapes directly in terms of range and possible statistical distribution of active-layer thickness. Moreover, for many climate-change related studies it is necessary to evaluate the ecosystem response to projected atmospheric climate.

Another problem is related to availability of active-layer measurements corresponding to particular climatic conditions. PDFs are usually assessed from histograms of empirical observations. The shape of the histogram and corresponding PDF depend to some extent on the number of class intervals employed, introducing subjectivity to the method if only a few samples are obtained. Because active layer measurements are conducted at different times and may correspond to different combinations of climatic parameters within a single landscape unit (Klene et al. 2001), they should be standardized to utilize all available information and to increase sample size.

Consistency in the large-scale spatial variability of thaw depth through time reported in several studies (e.g., Brown et al. 2000; Hinkel & Nelson, 2002) indicates the existence of localized controls related to combinations of surface and subsurface characteristics. Relations between the spatial variability of vegetation and thaw depth demonstrate that these controls can be represented by regional variations in landcover and physiographic units. These findings indicate that it is feasible to statistically characterize landscapes in terms of landcover-specific parameters representing the response of the ground thermal regime to both climatic forcing and such local factors as lateral variation in soil properties, moisture conditions, and vegetation.

The Stefan solution for the heat-transfer problem can be used as simple and effective tool to evaluate landscape-specific response. In its most basic form the Stefan solution can be written as a linear relation

between an “edaphic term” (E) involving soil moisture and thermal properties and a “climatic term” expressed as the thawing index (DDT) expressed in °C days (Nelson & Outcalt, 1987; Anisimov et al. 2002). This form of the Stefan relation for the depth of thaw (z_{th}) can be written:

$$z_{th} = E(DDT)^{1/2} \quad (1)$$

The “edaphic term” E is given by

$$E = \left(\frac{2\lambda ns}{Q_{ph}} \right)^{1/2} \quad (2)$$

where n is the dimensionless ratio of seasonal ground-surface and air degree-day sums, known as the “n-factor,” λ is the thermal conductivity of thawed soil ($\text{Wm}^{-1} \text{ } ^\circ\text{C}^{-1}$), $s = 86,400$ (s days^{-1}) is a time conversion factor, and Q_{ph} is the volumetric latent heat of fusion (J m^{-3}). In this representation the edaphic term E accounts indirectly for the surface and subsurface parameters that influence seasonal thaw and can be used to assess landscape sensitivity to the climatic forcing represented by the quantity $DDT^{1/2}$. The linear form of (1) allows empirical estimation of the E coefficient, if adequate information is available to correlate active-layer thickness with climatic observation for major generalized landscapes.

Values of the edaphic term E associated with different combinations of the landcover and physiographic units were calculated through individual active layer measurements at corresponding sites and the climatic term $DDT^{1/2}$, estimated from air temperature records. Five-year averages of the edaphic factor were calculated for each active-layer sampling location and used to investigate variations in E associated with spatial variations in surface and subsurface conditions within each landcover and physiographic unit. Landcover-specific statistics of E are presented in Table 1.

Histograms of the E coefficient for each generalized landscape unit are shown in Figure 3.

Table 1. Spatial variations of edaphic parameters for each generalized vegetation class.

Veg	N	Mn	Md	Min.	Max.	StD	Var. (%)
<i>Coastal Plain</i>							
MNT	247	2.12	1.99	1.41	4.65	0.52	24.63
WET	184	2.51	2.39	1.56	4.43	0.58	23.26
<i>Foothills Combined (1 km² and 1 ha sites)</i>							
MNT	123	2.16	2.13	1.36	3.05	0.34	15.98
MAT	313	1.70	1.70	1.20	2.50	0.25	15.03
SHR	304	1.78	1.76	1.02	2.71	0.32	18.13
WET	71	2.08	2.05	1.56	3.37	0.29	13.79

Mn – Mean; Md – Median; StD – Standard Deviation; Var. – Variance.

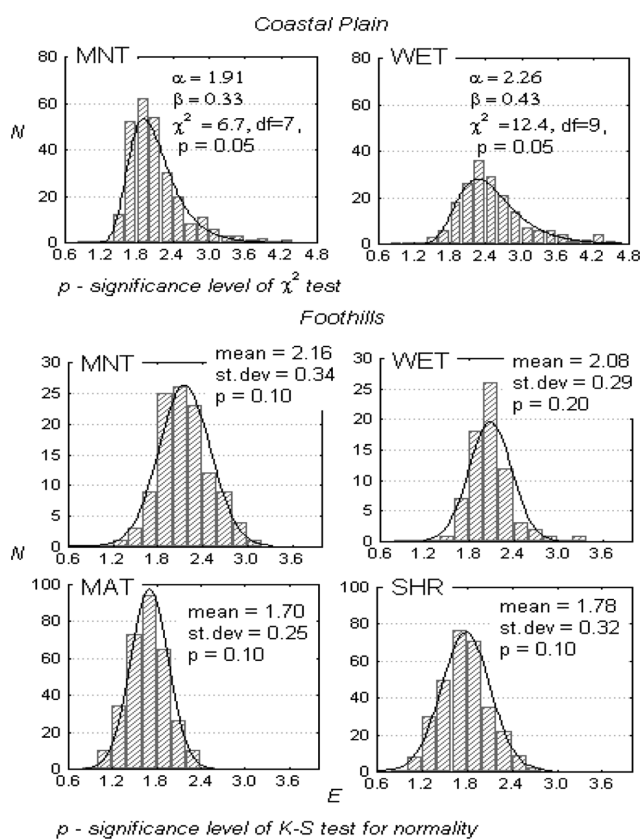


Figure 3. Histograms of the edaphic term E for each land-cover category and physiographic province.

The Kolmogorov-Smirnov test statistic, used to assess goodness of fit, indicates that the edaphic parameter is distributed normally for all vegetation categories in the foothills (significance level and parameters of distribution are shown in Figure 3).

Coastal-plain locations, however, experience significant deviation from normality. On the coastal plain, the empirical frequency distributions are positively skewed for both moist nonacidic and wet tundra, in response to higher thawing rates within drained thaw lake basins. The extreme distribution was fitted to histograms of E for coastal-plain landscapes. The extreme distribution has a cumulative probability function (Dmitriev, 1995, p 89) given by:

$$\begin{aligned}
 \text{extreme}(x) &= \frac{1}{2} \cdot \exp\left\{\frac{-(x-a)}{\beta}\right\} \\
 &\times \exp\left\{-\exp\left\{\frac{-(x-a)}{\beta}\right\}\right\}
 \end{aligned} \quad (3)$$

where α is a location parameter characterizing the position of the distribution along the x axis and β is a scale parameter, responsible for the stretch of the distribution. The histograms of E coefficients obtained for the moist nonacidic and wet tundra categories on the coastal plain, corresponding extreme distributions from equation (3), with α and β parameters estimated

from empirical data, and χ^2 (chi-squared) goodness-of-fit test statistics are shown in Figure 3.

5 CONCLUSIONS

Results presented in this paper indicate that distinct statistical regimes of active-layer thickness are associated with each landscape unit. It was demonstrated that spatial variability of the active layer corresponds well to that of the landcover for all sites, indicating that the spatial variation of vegetation can be used as a good indicator of that for active-layer thickness over large areas. The edaphic parameter adequately represents the integrated effect of localized controls responsible for soil thermal response to climatic forcing in different environmental settings and can be used to evaluate landscape sensitivity to climatic forcing. These findings have important ramifications for more realistic active-layer characterization at continental or circumarctic scales.

Although landscape-specific regularities found in the active layer of the northern Alaska may not be valid for other areas, the methodology presented here can facilitate spatial active layer investigations throughout the Arctic. Currently, periodic active layer observations are conducted under the Circumpolar Active Layer Monitoring (CALM) program (Brown et al. 2000). CALM was developed during the 1990s to observe the response of the active layer and near-surface permafrost to climate change, and currently incorporates more than 100 active sites in the Northern Hemisphere. Detailed analysis of available spatially oriented active-layer measurements will make it possible to evaluate the statistical parameters of localized active-layer variability for each generalized landscape unit over extensive regions.

ACKNOWLEDGEMENTS

This research was supported by U.S National Science Foundation grants OPP-9612647 and OPP-0095088. The authors are grateful to A. Anisimov, and J. Schuenemeyer for their valuable consultations, to Anna E. Klene for her contribution to the field work, and to Sally Marsh and Joan Hahn for logistical support in all stages of the project.

REFERENCES

- Affleck, R.T. & Shoop, S.A. 2001. Spatial analysis of thaw depth. Technical report ERDC/CRREL TR-01-1, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

- Anisimov, O.A., Shiklomanov, N.I., & Nelson, F.E. 1997. Effects of global warming on permafrost and active-layer thickness: results from transient general circulation models. *Global and Planetary Change*, 15: 61–77.
- Anisimov, O.A., Shiklomanov, N.I., & Nelson, F.E. 2002. Variability of seasonal thaw depth in permafrost regions: A stochastic modeling approach. *Ecological Modeling* (in press).
- Auerbach, N.A., Walker, D.A., & Bockheim, J. 1996. Landcover of the Kuparuk River Basin, Alaska. Joint Facility for Regional Ecosystem Analysis, University of Colorado, Boulder, Colorado.
- Brown, J., Hinkel, K.M., & Nelson, F.E. 2000. The Circumarctic Active-Layer Monitoring (CALM) program: research designs and initial results. *Polar Geography* 24(3):165–258.
- Burgess, M., Smith, S.L., Brown, J., Romanovsky, V., & Hinkel, K. 2000. Global Terrestrial Network for Permafrost (GTNet-P): permafrost monitoring contributing to global climate observations. *Geological Survey of Canada, Current Research*, 2000-E14: 8 pp.
- Dmitriev, E.A. 1995. *Statistics in Soil Science*. Moscow University Press, Moscow, 319 pp., (in Russian).
- Everett, K.R. & Parkinson, R.J. 1977. Soil and landform associations. *Arctic and Alpine Research*, 9(1): 1–19.
- Gomersall, C.E. & Hinkel, K.M. 2001. Estimating the variability of active-layer thaw depth in two physiographic regions of north Alaska. *Geographical Analysis* 33(2): 141–155.
- Hinkel, K.M. & Nelson, F.E. 2002. Spatial and temporal changes patterns of active layer depth at CALM sites in northern Alaska, 1995–2000. *Journal of Geophysical Research-Atmospheres* (in press).
- Isaaks, E.H. & Srivastava, R.M. 1989. *An Introduction to Applied Geostatistics*. Oxford University Press, New York, 561 pp.
- Klene, A.E., Nelson, F.E., Shiklomanov, N.I., & Hinkel, K.M. 2001. The n-factor in natural landscapes: variability of air and soil-surface temperatures, Kuparuk River basin, Alaska, USA. *Arctic, Antarctic, and Alpine Research* 33(2): 140–148.
- Malevsky-Malevich, S.P., Molkontin, E.D., Nadyozhina, E.D., & Shklyarevich, O.V. 2001: Numerical simulation of permafrost parameters distribution in Russia. *Cold Regions Science and Technology*, 32(2001): 1–11.
- McNamara, J.P., Kane, D.L., & Hinzman, L.D. 1999. An analysis of an arctic channel network using a digital elevation model. *Geomorphology*, 29: 339–353.
- Muller, S.V., Walker, D.A., Nelson, F.E., Auerbach, N.A., Bockheim, J.G., Guyer, S., & Sherba, D. 1998. Accuracy Assessment of a land-cover map of the Kuparuk River basin, Alaska: considerations for remote regions. *Photogrammetric Engineering & Remote Sensing*, 64(6): 619–628.
- Nelson, F.E., Shiklomanov, N.I., Mueller, G.R., Hinkel, K.M., Walker, D.A., & Bockheim, J.G. 1997. Estimating active-layer variability over a large region: Kuparuk River Basin, Alaska, USA. *Arctic and Alpine Research* 29(4): 367–378.
- Nelson, F.E., Hinkel, K.M., Shiklomanov, N.I., Mueller, G.R., Miller, L.L., & Walker, D.A. 1998. Active-layer thickness in north central Alaska: systematic sampling, scale, and spatial autocorrelation. *Journal of Geophysical Research-Atmospheres* 103(D22): 28963–28973.
- Nelson, F.E. & Outcalt, S.I. 1987. A computational method for prediction and regionalization of permafrost. *Arctic and Alpine Research* 19(3): 279–288.
- Nelson, F.E., Shiklomanov, N.I., & Mueller, G.R. 1999. Variability of active-layer thickness at multiple spatial scales, north-central Alaska, USA. *Arctic, Antarctic, and Alpine Research* 31(2): 179–186.
- Pannatier, Y. 1996. *Variowin: Software for Spatial Data Analysis in 2D*. Springer, New York, 91 pp.
- Rossi, R.E., Mulla, D.J., Journel, A.G., & Franz, E.H. 1992. Geostatistical tools for modeling and interpreting ecological spatial dependence. *Ecological Monographs*, 62(2): 277–314.
- Shiklomanov, N.I. & Nelson, F.E. 2002. Climatic variability in the Kuparuk region, north-central Alaska: optimizing spatial and temporal interpolation in a sparse observation network. *Arctic* (in review).
- Wahrhaftig, C. 1965. Physiographic Divisions of Alaska. *U.S. Geological Survey Professional Paper* 482, 52 pp.
- Walker, D.A. & Bockheim, J.G. 1995. Vegetation-soil characterization at the 12 flux tower sites, ARCSS/LAII Flux Study, LAII Science Management Office, University of Alaska, Fairbanks.
- Walker, M.D., Walker, D.A., & Auerbach, N.A. 1994. Plant communities of a tussock tundra landscape in the Brooks Range foothills, Alaska. *Journal of Vegetation Science* 5(6): 843–866.
- Walker, D.A., Everett, K.R., Webber, P.J., & Brown, J. 1980. Geobotanical Atlas of the Prudhoe Bay Region, Alaska. Special Report 80–14, *U.S. Army Cold Regions Research and Engineering Laboratory*, Hanover, NH.