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Climatic Variability in the Kuparuk Region, North-Central Alaska: Optimizing Spatial and Temporal Interpolation in a Sparse Observation Network

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ABSTRACT. Air temperature fields are required as input to spatial models in ecology, geocryology, and biogeochemistry. Air temperature data from a sparse, irregular meteorological network in the Kuparuk region of north-central Alaska were interpolated spatially and temporally to provide a 13-year (1987–1999) series of thawing degree-day fields at 1 km^2 resolution. Procedures involved standardizing diverse temperature records and applying topographically and climatologically aided interpolation, using station data and digital elevation models, to incorporate the effects of local topography. The accuracy of the interpolation procedures was assessed using cross validation. Considering the number of data points used for interpolation, their distribution, and the size of the area, the combination of climatologically assisted and topographically informed spatial interpolation procedures provides adequate representation of the annual degree-day fields for the Kuparuk region. Spatially integrated mean absolute error does not exceed 3% in any year. To investigate the spatial distribution of interpolation uncertainties, the cross-validation errors obtained at each station for each year were interpolated spatially to a regular 1 × 1 km grid consistent with the degree-day fields.

Key words: Arctic, Alaska, air temperature, climate, climate variability, spatial analysis, spatial interpolation

RÉSUMÉ. Des champs de température de l’air sont nécessaires en tant que données en entrée pour les modèles spatiaux en écologie, géocryologie et biogéochimie. On a fait des interpolations spatiales et temporelles de données de température de l’air provenant d’un réseau météorologique épars et irrégulier situé dans la région de Kuparuk, au centre-nord de l’Alaska, afin d’obtenir sur 13 ans (1987–1999) une série de champs de degrés-jours de dégel à une résolution de 1 km^2. On a dû normaliser les divers enregistrements de température et appliquer l’interpolation assistée sur les plans topographique et climatologique, en recourant aux données des stations et à des modèles altimétriques numériques qui intègrent les effets de la topographie locale. La précision des procédures d’interpolation a été évaluée par validation croisée. Compte tenu du nombre de points de données qui ont servi à l’interpolation, de leur distribution ainsi que de l’étendue de la zone, la combinaison des procédures d’interpolation spatiale assistées sur le plan du climat et fondées sur la topographie offre une représentation adéquate des champs de degrés-jours annuels pour la région de Kuparuk. Pour chaque année, l’écart moyen intégré spatialement ne dépasse pas 3 %. Pour étudier la distribution spatiale des incertitudes d’interpolation, les erreurs de validation croisée obtenues à chaque station et pour chaque année ont été interpolées spatialement à une grille normale de 1 x 1 km qui concorde avec les champs de degrés-jours.

Mots clés: Arctique, Alaska, température de l’air, climat, variabilité du climat, analyse spatiale, interpolation spatiale

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INTRODUCTION

The understanding and modeling of ecosystem processes and their changes require accurate, high-resolution temporal and spatial representation of climatic conditions. In the polar regions, however, networks of weather stations with long-term records and good spatial coverage are uncommon. In such situations, estimation of climatic variables at unsampled locations is necessary to represent regional climate patterns adequately. Spatial interpolation methods are frequently used to determine the geographic structure of climatic parameters over extensive areas. Inconsistent or inappropriate interpolation procedures can lead to inconclusive or even misleading results. The net cooling of the Antarctic between 1966 and 2000 reported by Doran et al. (2002), for example, may be a result of inappropriate extrapolation of station data across large, data-sparse areas of the Antarctic (Turner et al., 2002). Optimized interpolation procedures are similarly relevant for the Arctic, where climate records are in many cases available only from sparsely distributed population centers, often in coastal locations.

In recent years, several spatially distributed fields of global meteorological data have been produced (e.g., Kalnay et al., 1996; Jones et al., 1999; Willmott and Matsuura, 2001). Although these fields are extremely useful as input to spatially explicit macro- and mesoscale models, their resolution (usually on the order of 1 to 0.5 degree of lat/long) are not sufficient for regional and landscape-level modeling. To address this problem, several attempts have

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been made to complement these fields with more detailed coverage of the Arctic region. Tveito and Forland (1999) used meteorological data from a well-distributed network of 1247 stations, combined with terrain information, to produce air temperature maps with 1 km^2 resolution for the Nordic countries. The same cell size was used by Fleming et al. (2000) to produce air temperature and precipitation fields for Alaska. By using a thin-plate spline interpolation procedure, meteorological data from 74 stations, and a digital elevation model, they were able to produce maps that accurately depict general climatic patterns. Although accuracy assessment indicated that reasonable results had been achieved, the results were biased toward populated areas and coastal regions, where model accuracy is expected to be high.

For localized investigations in remote areas of the Arctic, comprehensive standardized data sets are not available, and climatological, hydrologic, and ecological investigations frequently rely on meteorological measurements conducted in the field.

STUDY AREA

The Kuparuk region of north-central Alaska (Fig. 1) provides an example of a mesoscale region with a sparse meteorological network. The closest official (U.S. National Weather Service) station is at Barrow, approximately 250 km west of the Kuparuk region. Since the 1970s, the Kuparuk region has been the subject of extensive research. Until recently, however, no common systematic data collection and management strategy had been developed. Although several complex and integrated ecological research programs have been conducted within the region, climatic observations have been carried out primarily to provide supplementary information for work in various disciplines. Locations and measurement procedures were selected to suit the needs of individual research projects or teams and are limited in many cases to short field seasons over only a few years. Because climatic information is an important input parameter or driving force (or both) in many models, spatial and temporal interpolations are important first steps in converting highly irregular point data for use in spatial applications. Several interpolation methods based on different observational networks have been used for the Kuparuk region. Nelson et al. (1997) used records from nine stations with topography-adjusted polynomial regression to produce weekly degree-day fields. A spatially distributed active-layer model developed by Hinzman et al. (1998) and regional CO_2 flux estimates produced by Oechel et al. (2000) relied on daily spatial air temperature fields for summer 1995, interpolated using records from six stations in a topographically adjusted kriging procedure. A simpler approach was used by Hobbie et al. (1998), who divided the Kuparuk region into five latitudinal “slices” to model carbon cycling in the Kuparuk region. Mean annual temperature was assumed to be constant within each slice. Shiklomanov and Nelson (1999) provided gridded fields of mean annual temperature and annual temperature amplitude for 1996, using an approach similar to that of Nelson et al. (1997) with an updated temperature network.

Such diversity in methods and data used for interpolation may result in large differences in regional climatic fields, making it difficult to integrate and compare outcomes from models of interrelated ecosystem processes. In this paper, we describe procedures used to standardize climatic information from diverse sources, in order to examine spatial and temporal climatic variability in the Kuparuk region. The analysis is focused primarily on constructing a 13-year (1987 – 99) series of annual gridded thawing degree-day fields. The thawing degree-day sum is an important parameter required for many biological, hydrological, and geocryological applications. Its evaluation does not require winter temperature records, which are sporadic and in many cases unreliable in the Arctic because of difficulties in operating untended instruments during the Arctic winter.

DATA AVAILABILITY

The core of the data set consists of five years (1995–99) of continuous air and soil surface temperature observations obtained at 13 sites distributed along the north-south climatic gradient between Prudhoe Bay and Toolik Lake (Fig. 1). Each site was instrumented with several Onset™ portable data loggers connected to single probe-type thermistors. Each logger/thermistor system has an effective temperature range of -50˚C to +33˚C and resolution of approximately 0.32˚C. At each site, one thermistor was placed in a radiation shield approximately 2 m above the ground surface, and one to nine loggers were placed at the interface between mineral soil and organic material in various microtopographic positions within the site (Klene et al., 2001). Temperature measurements were collected at 15 min, 1 hr, or 2 hr intervals, depending on site, season, and year.

Climatic observations are also available for six currently operational sites established between 1985 and 1994 (Hinzman et al., 1998). At each site, a 10 m meteorological tower was used to support sensors reading air temperature. Relative humidity, wind speed, and wind direction at two or three elevations are available for some years at several sites. Meteorological variables were measured each minute and averaged or totaled with output recorded once per hour using Campbell Scientific™ data loggers (Hinzman et al., 1998). Air temperature measurements collected at 2 m height were used in this analysis.

Both air temperature networks were closely monitored by field personnel during the summer seasons; data loggers were serviced and downloaded periodically, facilitating reliable summer data records. The type of measurement equipment was not changed during the

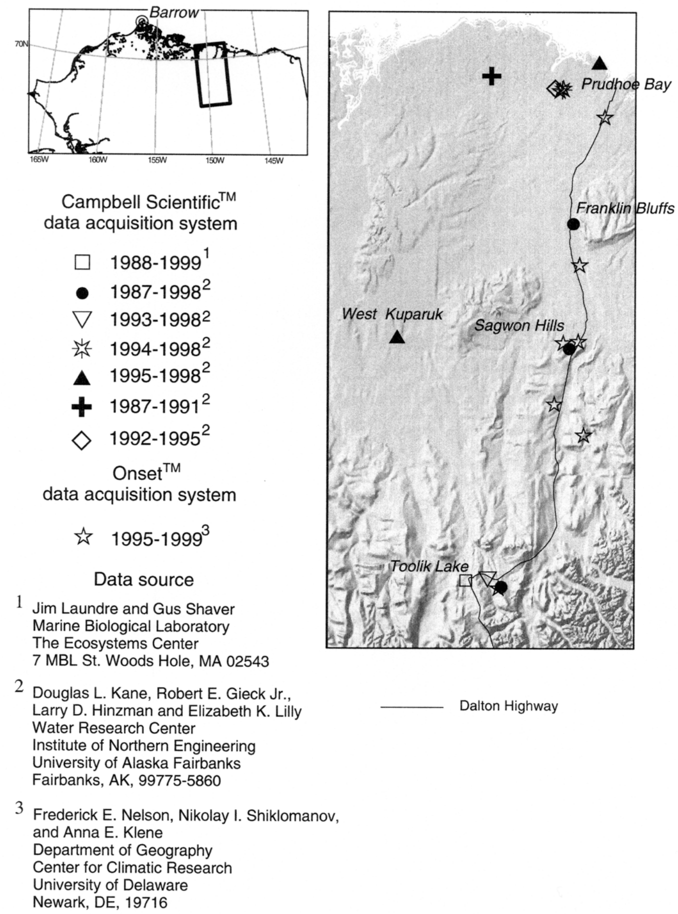

FIG. 1. Locations of sites (stations) of the climatological network in the Kuparuk region. Symbols indicate time periods when air temperature was measured at each site.

period of observation. Site locations and the periods of air temperature measurement corresponding to each are shown in Figure 1.

DATA ANALYSIS

The initial step of the data analysis included standardizing the air temperature records, which had been collected using different measurement procedures and equipment. Analysis was based on mean daily air temperatures series calculated for the summer period (1 June–31 August). Although more frequent measurements are available, the thawing degree-day sum is usually estimated by summing mean daily temperatures above 0˚C, providing standardization of daily records sufficient for the analytic methods employed in this study.

To compare records produced by equipment used in the different temperature networks, two sites with both types of equipment were selected. The West Dock site, established in May 1996, was initially instrumented with a 10 m meteorological tower supporting air temperature sensors and a Campbell Scientific™ data logger typical of the network used by Hinzman et al. (1998). At the end of June 1996, instrumentation at this site was supplemented with a smaller 2 m mast equipped with an Onset™ portable data logger/thermistor system. The two masts are approximately 10 m apart at locations with the same elevation (3 m) and similar ground cover conditions. A similar arrangement was constructed at the Betty Pingo site. Hinzman et al.'s (1998) equipment at this site has been operational since 1993; it was supplemented by an Onset™ portable system in June 1995. Measurement systems at Betty Pingo are located approximately 700 m apart, at locations with similar elevation (12 m). The Onset™-equipped site has moist, nonacidic vegetation (Walker and Everett, 1991; Walker et al., 1998), while the tower with Campbell Scientific™ equipment is located in a wetland. The relation between summer (1 June–31 August) mean daily air temperatures, as measured by the two systems at 2 m height, is shown in Figure 2. The strong correlation between measurements at each site is evident from Figure 2. The inexpensive Onset™ equipment underestimates air temperature, however, introducing a systematic negative bias when compared with the Campbell Scientific™ system, which has higher accuracy and resolution. Average daily differences (Campbell minus Onset) between air temperatures measured by different equipment at the two sites are shown in Table 1.

The difference in air temperatures recorded by the two types of equipment is consistent from year to year for the West Dock site, but varies for the Betty Pingo site. The larger distances between the towers equipped with different instrumentation, as well as differences in ground cover and soil moisture conditions, may be responsible for the larger interannual variations at the Betty Pingo site.

However, the four-year mean of the bias (0.7˚C) is consistent with that observed at the West Dock site. To standardize summer air temperature records produced by the Campbell Scientific™ and Onset™ instruments, the value of 0.7˚C was added to all mean daily temperatures recorded by the Onset™ system for 1 June–31 August of each year. The degree-days of thawing for the summer were estimated from standardized air temperature records by summing all positive values of mean daily temperatures during 1 June–31 August for each year at each station. The summer degree-days were used in all subsequent analyses.

SPATIAL INTERPOLATION

Methodology

Traditional geostatistical methods of spatial interpolation are based on functional relationships between interpolated values at unsampled locations and known values from neighboring stations, each of which influences parameters at the location of interest (Isaaks and Srivastava, 1989). The interpolation function depends on the interpolation method. Spatial regression (Myers, 1990), thin-plate splines (Eckstein, 1989; Hutchinson and Gessler,

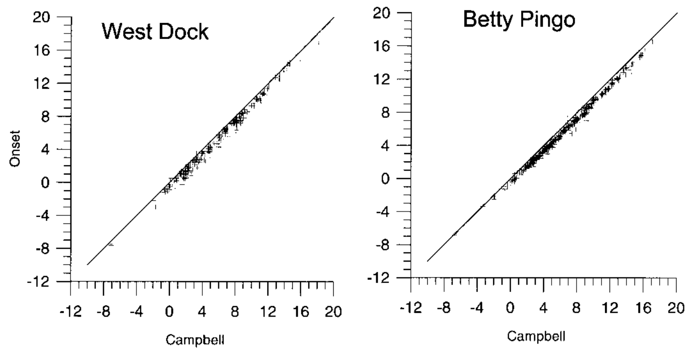

FIG. 2. Relations between mean daily air temperatures (˚C) measured by Onset™ and Campbell Scientific™ data logger systems at the West Dock and Betty Pingo sites.

1994), kriging (Ishida and Kawashima, 1993), and inverse-distance weighting (Legates and Willmott, 1990) are used most frequently. The diversity of climatic conditions in the Kuparuk region, a consequence of its areal extent and complex terrain, requires a relatively dense and even distribution of data points to produce reliable spatial fields of degree-days using geostatistical methods that rely only on spatial correlation between sample points.

As Figure 1 shows, however, the spatial distribution of the data points (stations) is very sparse. Accessibility issues governed site selection. With few exceptions, stations are located close to the only north-south road in the Kuparuk region. As a result, most data points are aligned along a north-south transect in the eastern part of the region, while the western part is significantly undersampled. Under such conditions, approaches to interpolation that make use of additional information that is spatially correlated with air temperature and simple physical principles have a clear advantage.

One way to enhance geostatistical interpolation of air temperature is to exploit the relationship between air temperature and elevation. A medium-resolution (300 × 300 m pixel size) digital elevation model (DEM) of the Kuparuk region, produced by the USGS and the North Slope Borough, makes this feasible. The effects of topography on air temperature interpolation have been treated statistically by several authors (e.g., Ishida and Kawashima, 1993; Fleming et al., 2000). However, for this research we adopted a more physically meaningful yet straightforward approach, used by Willmott and Matsuura (1995), Nelson et al. (1997), Hinzman et al. (1998), Tveito and Forland (1999), and Shiklomanov and Nelson (1999). The method takes advantage of the systematic variation of air temperature with elevation, based on simple meteorological (lapse rate) theory. The approach first estimates the air temperature at sea level for each station where measurements are available, using an environmental lapse rate of -6.5×10^{-3} ˚C m^{-1} and station elevation. Spatial interpolation can then be used to interpolate sea-level temperature to each node of the DEM. Finally, the air-temperature field is reconstructed using elevations obtained from the DEM for each pixel and the specified lapse rate. This set of procedures, termed "topographically informed interpolation" (TII), reduces interpolation error relative to more traditional techniques (Willmott and Matsuura, 1995).

TABLE 1. Mean daily differences (ºC) between air temperatures from two air temperature measurement systems (Onset™ minus Campbell Scientific™).

Site/Year	1995	1996	1997	1998	Average
West Dock		0.70	0.76	0.72	0.73
Betty Pingo	0.97	0.56	0.78	0.58	0.72

Interannual irregularities in the number and spatial distribution of stations in the Kuparuk region can, however, cause difficulties for direct comparison of temperature or degree-day fields produced annually. Figure 3a shows the number of available stations for each of the 13 years of interest (1987–99). The number of stations varies from 4 in 1987 to 18 in 1995–98. Such large inconsistencies can introduce significant bias into annual fields.

Bias can be minimized by use of a second air temperature field (in this case, degree-day) that is observed over a different time period using a network with higher spatial resolution (Willmott and Robeson, 1995). In many instances, station climatologies, produced by averaging air temperature (degree-days) for each station over the period of the available data record, can act as a substitute for a higher-resolution network. Termed "Climatologically Aided Interpolation" (CAI), the procedure uses the fact that the station climatology serves as a good air-temperature predictor for any particular year without actual data (Willmott and Robeson, 1995). Thus, CAI can significantly improve interpolation results. The approach involves interpolating climatologically average air temperatures (degree-days) estimated in a higher-resolution network of stations and calculating their annual deviations from the climatologies for each year observed in lower-resolution networks. The annual anomalies are then interpolated, and annual fields are produced by adding the annual anomalies to the climatology field.

To reduce interpolation error further, the climatologically aided interpolation can be combined with topographically informed interpolation, because CAI and TII procedures explain correlated but somewhat different components of the total spatial variance (Willmott and Matsuura, 1995). In combination, CAI and TII are used to produce climatological and annual anomaly fields, leading to improvements in the spatial accuracy of the resulting fields. This combined approach was adopted to produce annual summer degree-day fields for the Kuparuk region for the period 1987–99.

Interpolating Procedure

Degree-day totals, calculated for the period 1 June–31 August of each year at all stations in Figure 1, were scaled to sea level using station elevations derived from the DEM, the standard environmental lapse rate (-6.5×10^{-3} ˚C m^{-1}), and the standardized thawing period of 88 days. DEM-derived station elevations were used to maintain consistency in all aspects of the study. Although the average summer lapse rate in the Arctic is lower than -6.5×10^{-3} ˚C m^{-1} (C. Willmott, pers. comm. 2001), use of the standard environmental lapse rate for interpolation of the thawing degree-day fields is justified by the fact that degree-days are estimated using only positive daily air temperatures.

Although the total annual number of thawing days shows significant interannual variability in the study area, this variability occurs primarily in May and September and has relatively little effect on seasonal degree-day sums (Zhang et al., 1996, 1997). The number of thawing days occurring in the June-August period is much smaller. Numbers of thawing days for the period 1 June–31 August, averaged over all stations, are shown in Figure 3b. Deviations from the mean do not exceed three days in any year. Slightly negative mean daily air temperatures usually occur at the beginning of June and the end of August, but these do not have a significant effect on total summer degree-day accumulations. For consistency, the 13-year mean number of thawing days (88 days) was used to estimate degree-days of summer thawing for all years.

The 300 × 300 m DEM was transformed to a regular grid of 1000 × 1000 m cells by first increasing its resolution to 50 m through pixel duplication, and then contracting by calculating average elevation within each 1 km^2 grid cell. The pixel duplication procedure involved dividing each 300 × 300 m cell into 36 50 × 50 m pixels. The resulting image has the same amount of information but increased spatial resolution achieved by expanding the number of smaller pixels (Berry, 1993).

The degree-day climatologies were calculated by averaging annual summer degree-days of thawing for stations with a period of record longer than three years. Annual deviations from climatologies at each station were calculated by subtracting climatologically averaged degree-day values from annual values. The resulting climatological network consists of 19 stations (Fig. 1). The number of stations available for each of the 13 years ranges from 4 to 18 (Fig. 3a).

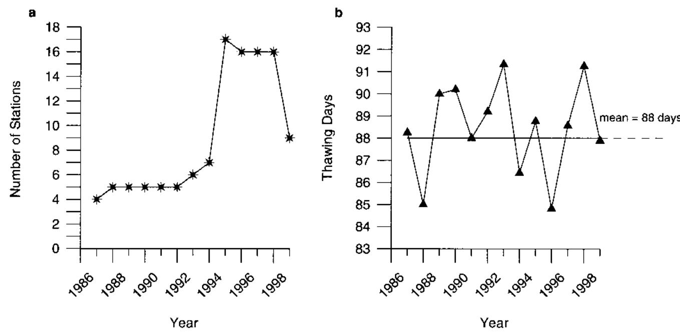

FIG. 3. (a) Number of available stations in Kuparuk climatological network for each year of study. (b) Summer (1 June–31 August) thawing days by year, averaged over the number of stations in the Kuparuk region.

Geostatistical Analysis

Climatologically averaged sea-level summer degree-day values for the 19 stations were used to estimate distances over which clear correlation exists in thawing degree-day values. This can be accomplished through construction of *variograms*, which summarize relationships between statistical variance and lag, or separation distance (Isaaks and 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 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 where 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. The spatial dependency model is constructed by fitting a function to an empirically derived variogram. Variogram modeling was accomplished in this study using the widely available VARIOWIN software package (Pannatier, 1996).

A sample variogram provides a quantitative summary about correlation of all data points separated by a certain distance, resulting in a single variogram value for each separation distance. The small number of data points employed in this study does not, however, allow construction of variograms with clear dependency structure. Analysis of spatial continuity of summer degree-days was based instead on variogram clouds. Variogram clouds are constructed by matching each sampled data point with each and every other sample data point to produce a variogram value for each resulting pair. These devices show the relationship between the magnitude of pair separation distance and variogram value for that pair (Isaaks and Srivastava, 1989; Pannatier, 1996). A sample variogram can be considered as the moving average of the variogram cloud. The cloud formed by variogram values and separation distances can be useful for gaining insight into the structure of spatial continuity for small, sparsely distributed data sets (J. Schuenemeyer, pers. comm. 2001).

Variogram clouds for climatologically averaged sea-level degree-days and the fitted spatial dependency model are shown in Figure 4a. Figures 4b and 4c show variogram clouds of sea-level degree-day climatologies along the north-south and east-west axes. Variability along the N-S dimension is much greater than along the E-W axis. The strong north-south climatic gradient in the Kuparuk region, reported by several researchers (Haugen, 1979, 1982; Zhang et al., 1996; Nelson et al., 1997), partially explains the pronounced spatial variability of degree-day totals in this direction. A change in spatial variability with direc-

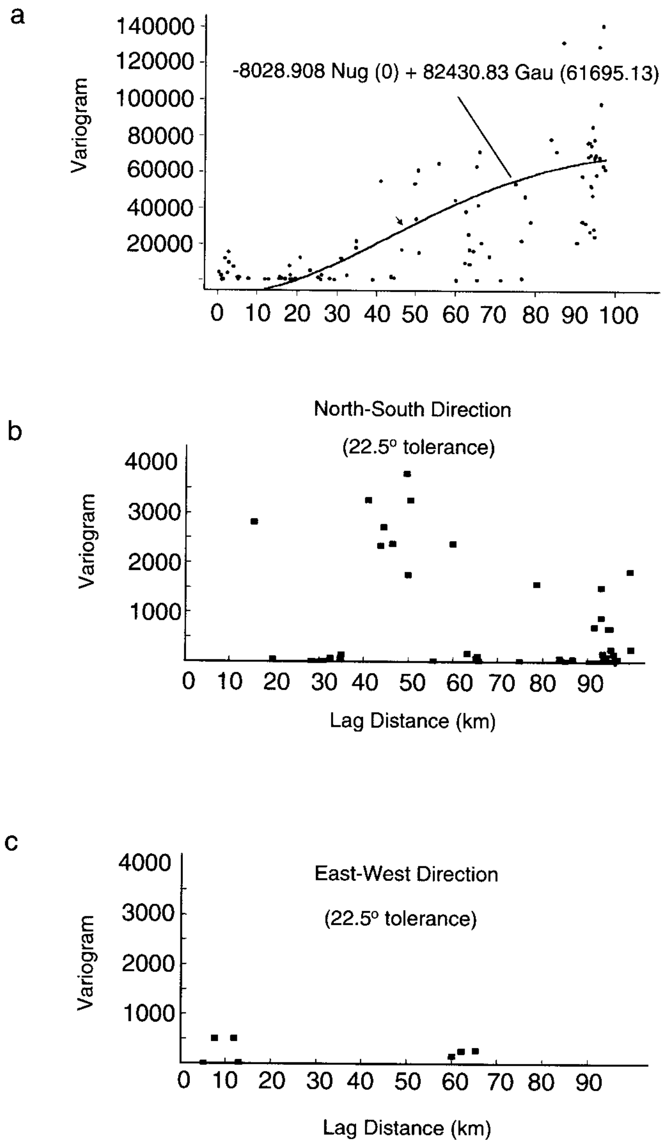

FIG. 4. (a) Variogram cloud and spatial dependency model. (b, c) Directional variogram clouds for summer sea-level degree-day climatologies for 1987–99, estimated from variable-length air temperature record obtained at 19 stations in the Kuparuk region.

tion (anisotropy) is accounted for in the model by adjusting the ratio of the range in the direction of minimum variability (east-west in this case) to that of maximum variability (Pannatier, 1996). To account for pronounced anisotropy, the ratio of 0.6 was applied to the spatial continuity model. The spatial continuity model was applied in ordinary kriging to interpolate sea-level degree-day climatologies to every node of the resampled DEM.

The small number of data points available in the majority of years prevented development of a spatial continuity model for each of the 13 annual anomalies. Variability models developed for the four years with relatively large numbers of data points (1995–98) indicate that the general structure of the spatial continuity is similar to the variability model developed for degree-day climatologies. The spatial model (Fig. 4a) was used in ordinary kriging to interpolate annual anomalies at sea level. Kriging was accomplished using a set of geostatistical FORTRAN routines from the GSLIB software library (Deutsch and Journel, 1992).

Interpolated sea-level climatologies were added to spatial coverages of the annual sea-level degree-day anomalies. Finally, degree-days at each grid point were estimated using DEM elevation data, the environmental lapse rate (-6.5×10^{-3} ˚C m^{-1}), and the length of the thawing period (88 days).

RESULTS

The 13-year (1987–99) series of gridded thawing degree-day fields for the Kuparuk region is shown in Figure 5. Because all data were collected over the land, and only the terrestrial component of the degree-day field is relevant to the present study, the ocean component was masked.

The general spatial pattern of degree-days is clearly seen on the map of the 13-year average. The spatial form of the degree-day field reflects two factors: topography and continentality. On the coastal plain, which has low relief, the degree-day field is relatively uniform, and continentality plays the major role in the form of the temperature field. The NE–SW gradient is apparent in all annual fields. Farther south, in the foothills and northern Books Range, the pattern of summer degree-days becomes more complicated in response to topographic complexity. Higher elevations generally have smaller degree-day accumulations in summer than do broad river valleys at lower elevations. The smallest number of degree-days is found in the southernmost portion of the map. This area is occupied by the high mountains of the northern Brooks Range, where temperatures remain close to 0˚C throughout the summer. Although the general spatial degree-day pattern is similar from year to year, some deviations are evident on the 1994 map. For this year, a strong east-west gradient is present in the central part of the region. This anomaly cannot be attributed to the interpolation procedure alone. Although there were fewer stations in 1994 (Fig. 3a), their spatial distribution is almost identical to that of 1995–98. However, the number of degree-days accumulated in the eastern part of the region in 1994 is higher than that recorded at stations in the western part. Although the positive degree-day anomaly is located around the Franklin Bluffs and Sagwon Hills sites (Fig. 1), no change in equipment, measurement procedure, or equipment malfunction that could explain the increase in air temperature was recorded in 1994 at those locations.

Pronounced interannual variability is apparent from Figure 5. Figure 6a shows interannual variations of area-averaged summer degree-days. Spatially integrated degree-days show large deviations from the 13-year, area-averaged mean (807˚C days). Maxima occurred in

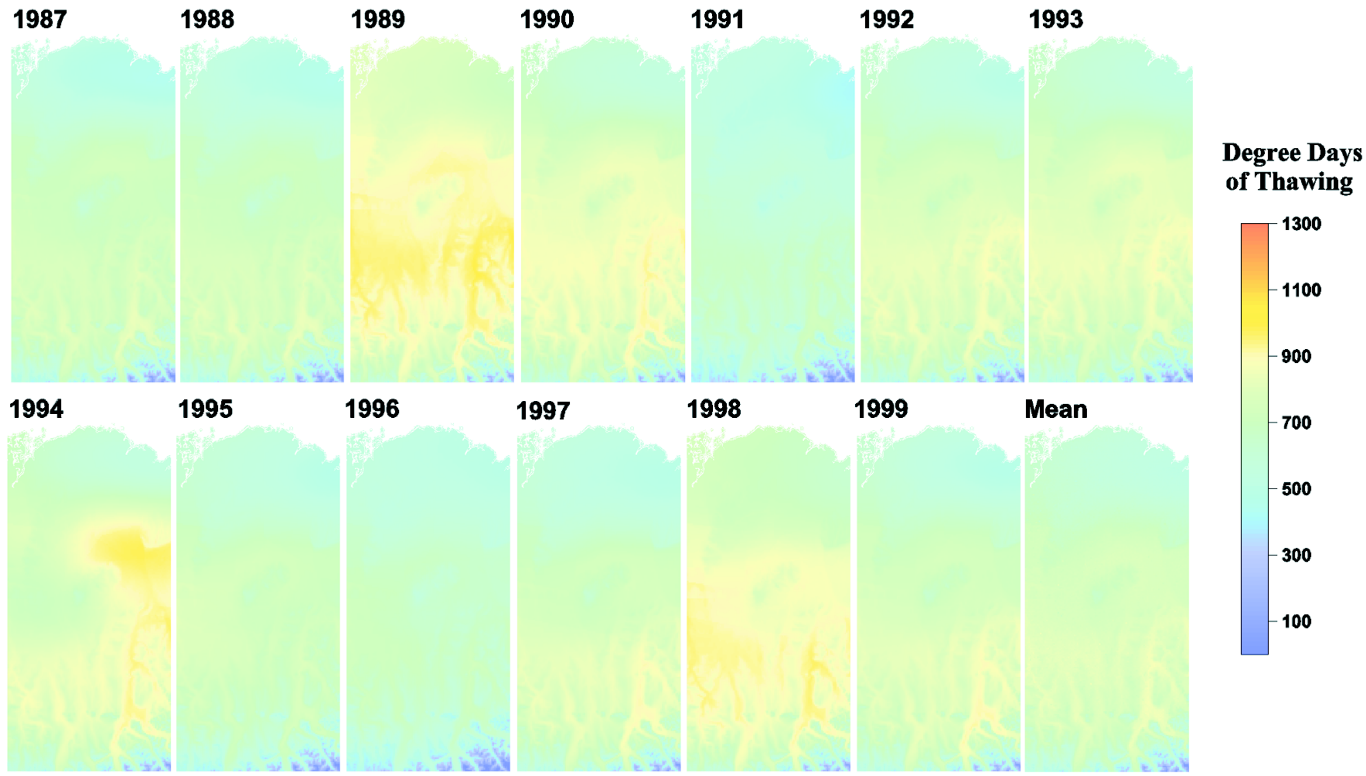

FIG. 5. A 13-year series (1987–99) and 13-year mean of gridded thawing degree-day fields for the Kuparuk region.

1989 (970˚C day), 1994 (881˚C days), and 1998 (922˚C days), while minima were reached in 1987 (752˚C day), 1991 (652˚C days), and 1996 (687˚C days). No significant monotonic trend is detectable during the 13-year period.

VALIDATION AND ERROR ANALYSIS

Because all climatic data were used in the interpolation procedure, no data are available for formal validation of the resulting degree-day fields. Ordinary kriging, which was applied to interpolate sea-level degree-day climatologies and annual anomalies, can produce fields of variances that can be used as accuracy estimates (Isaaks and Srivastava, 1989). However, these estimates can be misleading because they do not account for the effect of topographically informed and climatologically aided procedures, which tend to reduce the errors (Willmott and Matsuura, 1995; Willmott and Robeson, 1995). In such situations, cross validation can be used to evaluate the uncertainty associated with the interpolation method (Amorocho and Espildor, 1973). Cross validation deletes an individual sample point and uses the remaining data points to predict its value, allowing prediction error to be inferred from the difference between the predicted and original sample values. This can be repeated over all sample data points, and the differences mapped for all data locations. The purpose of checking the interpolation procedure with cross validation is to view where the procedure may encounter predictive difficulty. Cross-validation errors can exceed actual interpolation error, because the network of stations is degraded to *n-1* stations, making it sparser. This is especially true for networks with very small numbers of poorly distributed stations. In this case, real interpolation accuracy can be better than that reported from cross validation.

The station Mean Absolute Error (MAE), the maximum and minimum absolute errors obtained from cross validation, and the number of stations are presented in Figure 6b. Comparison of absolute errors with the number of stations for each year indicates that, although variations in network size can be significant, there is no obvious error correlation with these variations. The station MAE does not exceed 40 degree-days for any year, while individual stations can produce maximum absolute errors reaching 102 degree-days. These results are acceptable, considering the number of data points used for interpolation, their distribution, and the size of the area.

To investigate the spatial distribution of interpolation uncertainties, the cross-validation errors obtained at each station for each year were interpolated spatially to a regular 1 × 1 km grid consistent with the degree-day fields. An attempt to use ordinary kriging was made to produce error fields. However, the small number of data points for some years did not allow development of an adequate spatial continuity model on an annual basis. Analysis of variograms for the years 1995–98 indicates that the spatial dependency structure of errors varies dramatically from year to year. Because results produced by kriging can vary signifi-

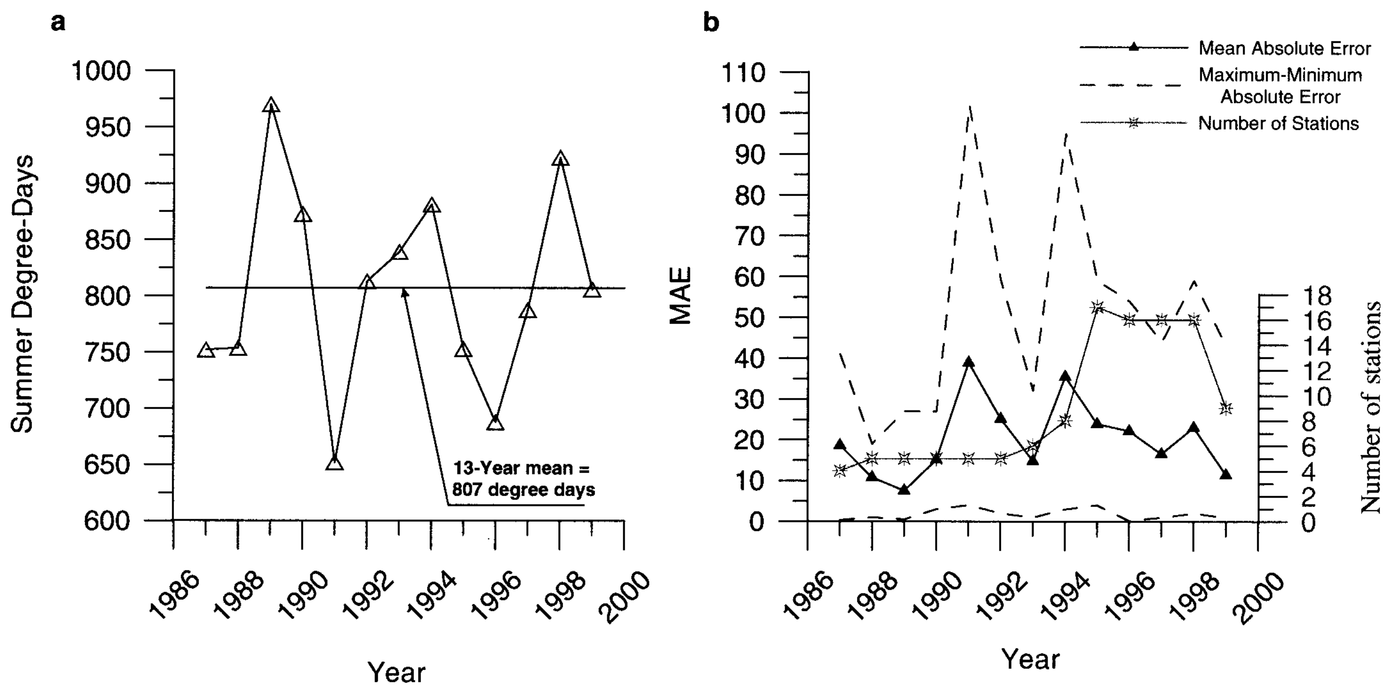

FIG. 6. (a) Interannual variations of summer degree-day sums, area-averaged over Kuparuk region. (b) Mean, maximum, and minimum station cross-validation errors and number of stations in Kuparuk climatological network.

cantly, depending on the variability model selected for interpolation, the standard inverse distance to second power method (Isaaks and Srivastava, 1989) was used to construct uncertainty fields.

Annual error fields are shown in Figure 7. The magnitude and spatial distribution of errors varies from year to year. Large positive errors are associated with 1991 and 1992, while the largest negative error was found for 1994. The largest errors are consistently encountered at a single point in the west-central part of the region (West Kuparuk station) and at the Franklin Bluffs station located in the east-central area (Fig. 7). The large cross-validation errors attributed to the West Kuparuk station are associated primarily with distance to other data points. The Franklin Bluffs station is located on the flood plain of the wide, braided Sagavanirktok River, at the base of a relatively high bluff. The combination of close proximity to the water and screening by the high topographic feature produces highly unusual microclimatological conditions at the Franklin Bluffs station, which are not adequately resolved by the interpolating procedure. To examine the overall accuracy of the degree-day interpolation algorithm, spatial integration of the error fields was performed. Figure 8 is a graph of mean absolute error, and the maximum positive and negative errors, produced from spatial error integration on an annual basis, expressed in percent of the spatial degree-day means for individual years. The MAE does not exceed 3% in any year, while the maximum positive and negative errors do not exceed 16%.

Figure 7 indicates that the large cross-validation errors produced by the West Kuparuk station can introduce significant bias to the error fields for years when measurements are available at this location (1994–98). This is primarily because cross-validation errors for a poorly distributed station network indicate the importance of the station to the interpolating procedure, rather than a large degree of uncertainty associated with a particular isolated point. To eliminate this bias, the error interpolation can be repeated with error values from the West Kuparuk station removed. In this case the influence of the size and distribution of the station network should be more obvious and the years with larger numbers of stations and better distribution of data points should have less uncertainty associated with the degree-day fields.

CONCLUSIONS

Considering the number of data points used for interpolation, their distribution, and the size of the area, the combination of climatologically assisted and topographically informed spatial interpolation procedures provides adequate representation of the annual degree-day fields for the Kuparuk region. The spatially integrated mean absolute error does not exceed 3% in any year.

Although the interpolation algorithm minimizes the bias introduced to DDT fields by the uneven distribution of stations, large errors are associated with underrepresentation of the western portion of the region. The problem of filling critical gaps that exist in the current climate-monitoring network in the Kuparuk was recently addressed by installation of several automatic air/ground temperature monitoring systems in the western part of the region.

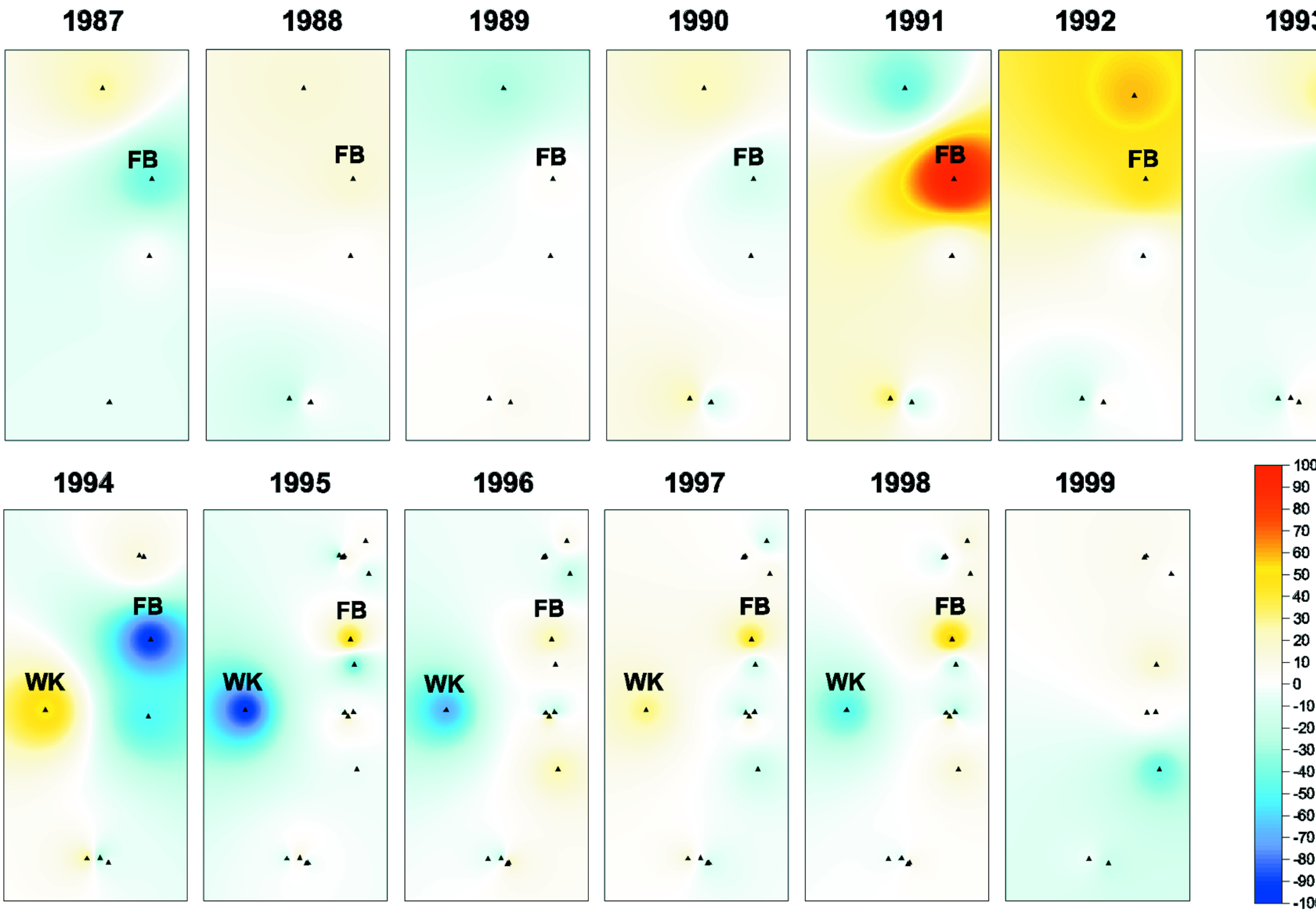

FIG. 7. Annual summer degree-day error fields, estimated by spatial interpolation of station-specific cross-validation errors in the Kuparuk region.

Because many regional models of ecosystem processes require air temperature as a primary input variable, the object of future research should be to develop long-term, gridded time series of monthly air temperature means for the Kuparuk region.

Constraints related to the availability of spatially and temporally harmonized observational data sets limit our ability to evaluate changes in the Arctic system. New techniques for assimilating meteorological observations into numerical weather-prediction models have facilitated reanalysis of long time series of major meteorological variables (Kalnay et al., 1996; Kistler et al., 2001). Although this approach provides spatially and temporally consistent climatic fields produced in almost real time, simplified representations of the physical processes used to derive reanalysis data sets significantly influence their accuracy. While satellite remote sensing holds great potential for provision of observational support of modeling and synthesis studies, no effective techniques are currently available for many crucial climatic and surface variables. Given the inherent limitations of reanalysis and remote sensing products, there are no substitutes for climatic data derived from surface-based in situ observations. Detailed region-based analysis, such as that presented in this paper, can contribute to development of better parameterizations that can be used subsequently for climate reanalysis and validation of remote-sensing products.

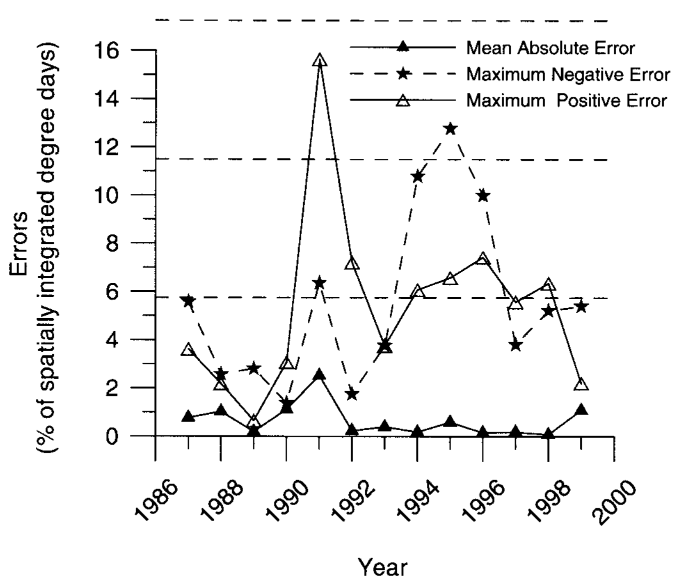

FIG. 8. Mean absolute error and maximum positive and negative errors, produced from spatial error integration on an annual basis, and expressed in percent of the spatial degree-day means for individual years.

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