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Winter Air Temperature Change over the Terrestrial Arctic, 1961–1990

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Abstract

We evaluate two approaches to spatially interpolating winter surface air-temperature fields over the terrestrial Arctic from available weather-station records. We then examine 30 yr (1961–1990) of winter air-temperature change over the terrestrial Arctic through a time-trend analysis of interpolated winter air-temperature fields. We used monthly average air temperatures from 4984 Arctic station records that were available for the period 1961–1990. The two spatial interpolation procedures employed were "traditional" interpolation and a method that makes use of spatially high-resolution digital-elevation information, called "DEM-assisted" (DAI). The Arctic average winter air temperature obtained from the traditionally interpolated 1961–1990 climatology is over 9°C colder than the mean winter station temperature, illustrating the considerable warm bias in Arctic weather station locations. The DAI-based average is 1°C colder, further emphasizing the importance of spatial interpolation prior to spatial averaging.

Over the 30 yr, increases in winter air temperature appear across western Canada and in parts of central Asia, with decreasing trends apparent over eastern Canada. Much of the Arctic exhibits no clear trend, with low explained variances. In western Canada, however, warming trends are on the order of 0.1 to 0.4°C yr^{-1} when the fields analyzed were traditionally interpolated or interpolated using DAI. Explained variances (r^2s) are higher where trends are largest: approximately 0.2 to 0.4 in western Canada and slightly higher (albeit spuriously) in an isolated area of central Asia. Over the entire terrestrial Arctic, mean winter air temperature has increased at a rate of about 0.05°C yr^{-1} based on traditional interpolation and DAI.

Introduction

Climate fields derived from meteorological observations have numerous applications in earth-system science (Karl et al., 1993, Willmott et al., 1996, Nelson et al., 1997). The challenge of accurately estimating precipitation and surface air temperature has been made all the more important because of the possibility of large- and regional-scale climate change (Jones et al., 1999, Nicholls et al., 1996, Overpeck et al., 1997, Przybylak, 1997). In its Second Assessment, the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al., 1996) estimated that global average surface air temperatures may rise 2 to 6°C by the year 2100, due mainly to increases in greenhouse gases. Climatic variables also are key inputs into physically based models of surface runoff (Vörösmarty et al., 1996) and evapotranspiration (Vörösmarty et al., 1998).

Recent General Circulation Model (GCM) studies of the effects of rising greenhouse gas concentrations projected significant increases in mean surface air temperature (Manabe et al., 1991, Nicholls et al., 1996), especially in the high latitudes. There also may be large changes in minimum daily temperatures (Zwiers and Kharin, 1998), and decreases in the diurnal variability of winter temperature in Northern Hemisphere midlatitudes. A general drying of midcontinental areas during summer and increased chance of drought are possible as well (Meehl et al., 2000).

Estimation of surface air temperature at the higher latitudes is a challenge because of the limited number of observation sites and available weather-station records (Rigor et al., 2000). Despite these deficiencies, analyses of surface air temperature in arctic regions are necessary to assess the existence and extent of prognosticated warming (Vörösmarty et al., 2001). Air temperature fields also remain important drivers of arctic hydrologic models, forcing both snowpack and permafrost active-layer dynamics. Although spatially representative arctic geophysical data sets remain scarce, a recent synthesis of observational evidence documented significant change (Serreze et al., 2000). Possible greenhouse-gas induced warming could likely lead to significant feedbacks in the arctic hydroclimatic system, such as increases in winter precipitation (Nicholls et al., 1996).

Among the few studies that have examined air-temperature trends within high-latitude weather-station records is Chapman and Walsh's (1993) analysis. They estimated surface air-temperature trends over the period 1961–1990 from a data set produced by the Climate Research Unit of the University of East Anglia. This data set—consisting of monthly air temperatures from land stations and sea-surface observations—was subjected to extensive quality control and subsequently consolidated onto a 5° × 5° latitude-longitude grid. Analysis of the gridded data showed that land-surface warming during the period 1961–1990 was greatest in winter (1.0 to 1.5 °C dec^{-1}) and spring (0.75 to 1.25°C dec^{-1}), with the most pronounced warming appearing over Alaska, northwestern Canada, and northern Eurasia. Przybylak (2000) analyzed data from 37 Arctic stations, 7 "subarctic" stations, and 30 0.5° grid cells and, conversely, found that increases in Arctic air temperature were more significant in the warm half of the year. These differences illustrate that the seasonality of warming remains unresolved. GCMs tend to project the largest increases in autumn and winter (Kattenburg et al., 1996), while observations over land show maximum warming in winter and spring. The largest increases appear from winter through summer over the Arctic Ocean (Serreze et al., 2000).

Our paper is also an attempt to help resolve uncertainties and conflicting conclusions about Arctic air temperature and air-temperature change. More specifically, we use two spatial interpolation

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TABLE 1

Source data sets and the number of available Arctic stations

Data Set	Number of stations	Time span
GHCN v. 2	2297	1701–1989
AES (Canada)	5115	1840–1993
Russia, State Hydromet	14	1934–1991
GC-NET	14	1995–1998
Automated Weather Station Project	6	1989–1995

methods to estimate and evaluate winter average air temperatures across the terrestrial Arctic (poleward of 45°N latitude) and within the Pan-Arctic drainage basin over the period 1961–1990. Our interest extends south to 45°N to include all areas within those drainage basins that discharge into the Arctic Ocean. We estimate and evaluate 30-yr linear trends across the terrestrial Arctic as well. The period 1961–1990 was chosen to make use of the relatively good spatial coverage offered by weather-station networks. Using alternative spatial estimation techniques (Willmott and Matsuura, 1995), we are able to reduce biases in the spatial means and variances as well as assess the spatial dimensions of winter warming.

Data

Merging several weather-station archives together can improve spatial coverage and aid in the estimation of spatially interpolated air-temperature fields (Jones, 1994, Peterson and Vose, 1997). In order to develop more representative air-temperature fields for the Arctic, elements of several existing archives were merged into a single source. Most of the stations selected were drawn from the (1) Global Historical Climatology Network (GHCN) version 2 and (2) Canada's Atmospheric Environment Service (AES) data sets. The GHCN v. 2 archive contains mean air-temperature data for a global network of 7280 stations. Of those stations, 2297 lie north of 43°N and were considered for inclusion in the merged archive. Although analyses are restricted to land areas north of 45°N, stations from as far south as 43°N are used to better resolve winter air temperatures near the southern boundary (45°N) of our study area. Spatial coverage attained from the Atmospheric Environment Service (1994) (AES) data set for Canada is considerably better than can be achieved from the GHCN v. 2 (or v. 1) archive.

Automated weather stations have become useful in gathering meteorological observations in harsh environments. Two such automated-station networks were set up on Greenland, and their records are included here. These two networks contain 14 station records from the Greenland Climate Network (GC-NET), archived at the University of Colorado (Steffen et al., 1996), and 6 from the Automated Weather Station Project (AWSP), available from the University of Wisconsin-Madison (Automated Weather Station Project, 1999). Collaboration with Russian scientists at the State Hydrometeorological Institute in St. Petersburg made possible the inclusion of 14 station records from near the Arctic coast. Their coastal location, however, limits their utility in resolving data-sparse areas of central Siberia. The data from Greenland, Russia, and Canada, when merged with the the GHCN v. 2 data (Table 1), improve the spatial coverage across the terrestrial Arctic.

Quality-control checks were performed on all station data to detect questionable observations. Station collocations were resolved by the removal of some station records, the truncation of other time series or, in a few cases, the correction of erroneous geographic coordinates. Collocation quality control helped condition the spatial network of temperature stations for use with exact spatial interpolators.

Monthly air-temperature time series that remained after collocation quality control and station merging were evaluated, both statistically and visually, for possible discontinuities and spurious extremes. This quality-control step involved identification of abrupt changes in the mean, extreme outliers (in both space and time), and runs of identical values. Discontinuities were evaluated statistically using the cumulative sum statistic (Peterson et al., 1998). Possibly discontinuous station time series were plotted along with the station records from the nearest two stations and visually compared. All suspect stations were visually analyzed for extreme observations that were not present in the nearby station records. The 5 source data sets appeared to be very well conditioned, and no correction was needed.

Simple checks were performed to reveal consecutive identical values as well as extreme observations. Extreme observations were evaluated statistically with a z-score. A critical value of the statistic (7.0) was chosen to separate unrealistic deviations (errors) from statistically extreme but plausible air temperatures. No discontinuity was detected using this or other methodologies suggested by Peterson et al. (1998). Observations with z-scores exceeding 7.0, however, were recorded as missing in our quality-controlled version of the database.

Following quality-control assessments, a total of 6487 station records located north of 43°N were retained (Fig. 1a). A subset of these records, 4984 of them, contained data for the period 1961–1990 and were used to evaluate winter air temperature over the terrestrial Arctic (Section Results). As with the source data sets, the spatial distribution of the stations remains uneven, with high-resolution representation in the mid latitudes of North America and Europe and relatively coarse station networks in the higher latitudes (Fig. 1a and b).

Methods

Interpolation of monthly air temperature, from the irregularly spaced station data to the nodes of a regular spherical grid, was accomplished using a modified version of Shepard's (1968) inverse-distance weighted interpolation algorithm. The grid resolution chosen was 0.5° of latitude by 0.5° of longitude. This interpolator incorporates spherical geometry, accounts for uneven clusterings of stations, and allows for extrapolation beyond the range of station data near a grid point (Willmott et al., 1985). Our interpolator is governed by

$$\hat{T}_j = \frac{\sum_{i=1}^{n_j} (T_i + \Delta T_{ij}) w_{ij}}{\sum_{i=1}^{nj} w_{ij}} \tag{1}$$

where $\hat{T}_j$ is the interpolated air-temperature estimate at grid-point j, T_i is the observed winter air temperature at station location i, ΔT_{ij} represents our extrapolation increment at station i, w_{ij} is the influence that data-point i has on grid-location j, and n_j is the number of near-the-grid-point observations that influence $\hat{T}_j$. This is a "traditional" interpolator in that the only information that influences $\hat{T}_j$ is the station temperatures (T_is) and their geocoordinates.

Interpolation accuracy often can be improved through the use of ancillary data that are spatially correlated with the variable of interest (Robeson and Janis, 1998, Willmott and Matsuura, 1995). One can, for instance, enhance the interpolation of some air temperature fields by utilizing the relationship between air temperature and elevation, and a high-resolution Digital Elevation Model (DEM). Willmott and Matsuura (1995), for example, demonstrated that—for annual air temperature across the U.S.—a DEM-assisted interpolation (DAI) method was 24% more accurate than traditional interpolation. Air temperatures at the stations were increased to their sea-level equivalents, according to an average lapse rate of 6.5°C km^{-1}. The estimated sea-level temperatures then were interpolated to a latitude-longitude grid, and these were reduced according to their DEM elevations, again using the 6.5°C km^{-1} lapse rate.

It is important to note that the lapse rate of interest here is in surface air temperature, not in air temperature as it changes with height above the surface. As a consequence, studies of atmospheric lapse rates (commonly based on rawinsonde data) shed insufficient light on our problem and can be misleading. There is, however, a small, emerging literature on surface air-temperature lapse rates. In a study of surface air-temperature lapse rates along a transect in the Colorado Rockies, for example, Pepin and Losleben (2002) observed winter monthly average lapse rates of 7 to 8°C km^{-1}. Winter surface air-temperature lapse rates along a transect in the Pennines in England (Pepin et al., 1999)—an area that frequently experiences subarctic conditions—were similar, about 6 to 8°C km^{-1}. Such observations suggest that winter surface air-temperature lapse rates tend to be linear and similar in magnitude to the lapse rate (6.5°C km^{-1}) that we use. These studies further suggest that arctic rawinsonde data, which often show strong winter inversions, may significantly misrepresent winter surface air-temperature lapse rates.

In order to evaluate both the interpolator and the relative adequacy of a given station network, we used a cross-validation procedure (Efron and Gong, 1983, Willmott and Matsuura, 1995). This involves removing a station from the station network and then interpolating to it from its neighbors. The difference between the interpolated estimate and the observed station value is a measure of interpolation "error." This procedure is repeated (with replacement) for each of the n stations in the network. The cross-validation errors reflect both the ability of the interpolator to resolve the air-temperature field and bias induced by an ill-conditioned station network. It should be mentioned that cross validation may overestimate the actual interpolation error, since the network has been degraded to $n - 1$ stations.

Results

Traditional interpolation (described in Methods) was used to spatially interpolate station-mean winter temperatures onto a 0.5° latitude-longitude grid. Mean winter temperature for each year is the average of December, January, and February monthly average temperatures. The spatial domain of the interpolated fields includes nearly all land areas poleward of 45°N. Because of the limited amount of station data for the Greenland ice sheet prior to 1990, Greenland grid nodes were removed from both the spatial integrations and trend analyses to follow.

Climatologically averaged (1961–1990) winter temperatures show a strong east-to-west gradient across central and eastern Asia (Fig. 2a). The coldest region in the terrestrial Arctic is northeastern Eurasia, where winter average temperatures are often below –35°C. Across Greenland, a strong north-to-south temperature gradient is apparent, although the efficacy of this trend is questionable because the number of station records is quite limited. An area-weighted spatial integration of the gridded winter air-temperature means reveal a terrestrial Arctic mean winter air temperature of –18.25°C (Table 2), not including Greenland. The areal average for the Pan-Arctic basin (shaded in Fig. 1) is –23.74°C .

Associated interpolation cross-validation mean-absolute errors (MAEs) are highest in northeastern Asia, Greenland, parts of the Rocky Mountains in western Canada, northern Scandinavia, and the Alps in Europe (Fig. 2b). All of these regions have relatively high relief, suggesting that traditional interpolations tend to fail in sparsely sampled, complex terrain. Cross-validation errors are lowest in the relatively even, low-lying areas of central and eastern Canada and in central and western Asia. The spatially averaged cross-validation MAE for the terrestrial Arctic is 1.71°C , and 1.86°C for the Pan-Arctic drainage basin (Table 2).

Winter air temperatures also were interpolated to the 0.5° grid using DEM-assisted interpolation (DAI) (described in Methods). Average winter air temperatures estimated using DAI (Fig. 3a) are noticeably colder than traditionally interpolated temperatures (Table 2).

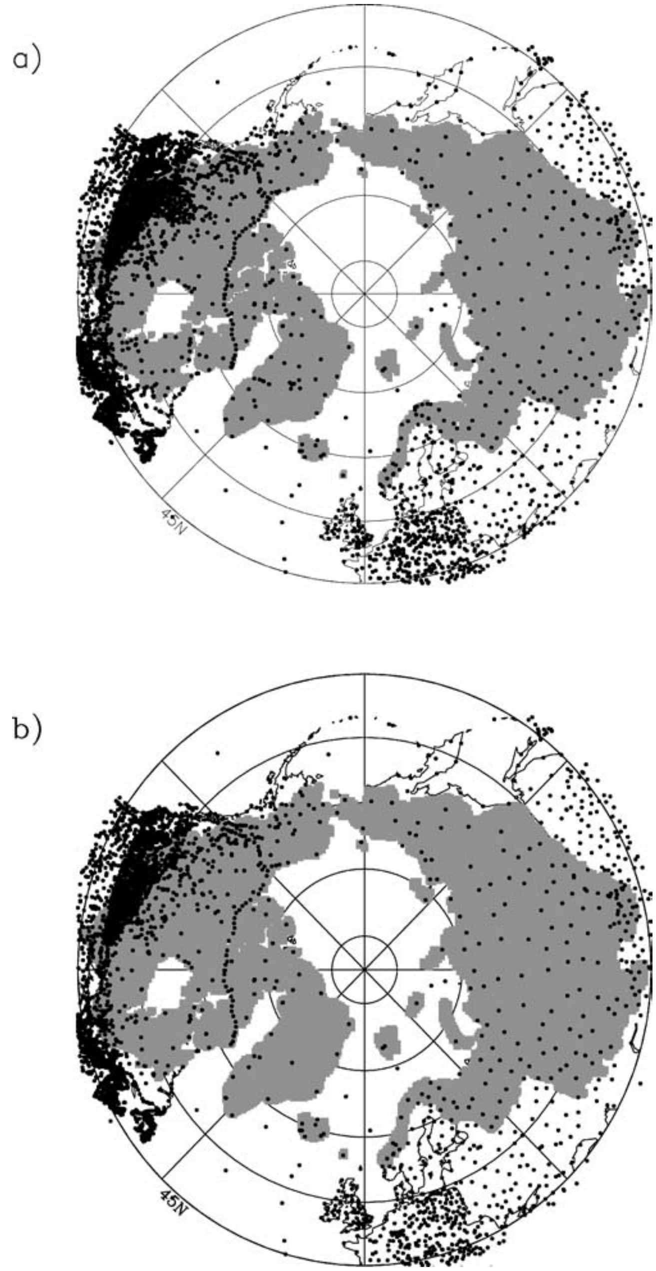

FIGURE 1. Locations of the monthly air-temperature station records for all Arctic stations (a) and for those Arctic stations with data from the period 1961–1990 (b). The light grey shading delineates the Pan-Arctic drainage basin. The map projection is Lambert's Azimuthal Equal Area.

This is particularly apparent in areas of high relief such as the Rocky Mountains and the high-elevation regions in east-central Asia. The most striking difference, however, is over Greenland, where DAI air-temperature estimates over the ice cap are as much as 10°C colder. The DAI estimates reveal large-scale patterns similar to those seen in the traditionally interpolated fields; however, when averaged by latitude, considerable differences are evident (Fig. 4). Averaged over latitude bands, the disparity can be as much as 2°C. Figure 4 also illustrates the considerable bias in station locations toward the mid latitudes, with over 85% of the climatology stations located south of 55°N latitude. The spatially integrated DAI winter mean temperature over the terrestrial Arctic (not including Greenland) is –19.24°C, about 1.0°C colder than the area mean obtained through traditional

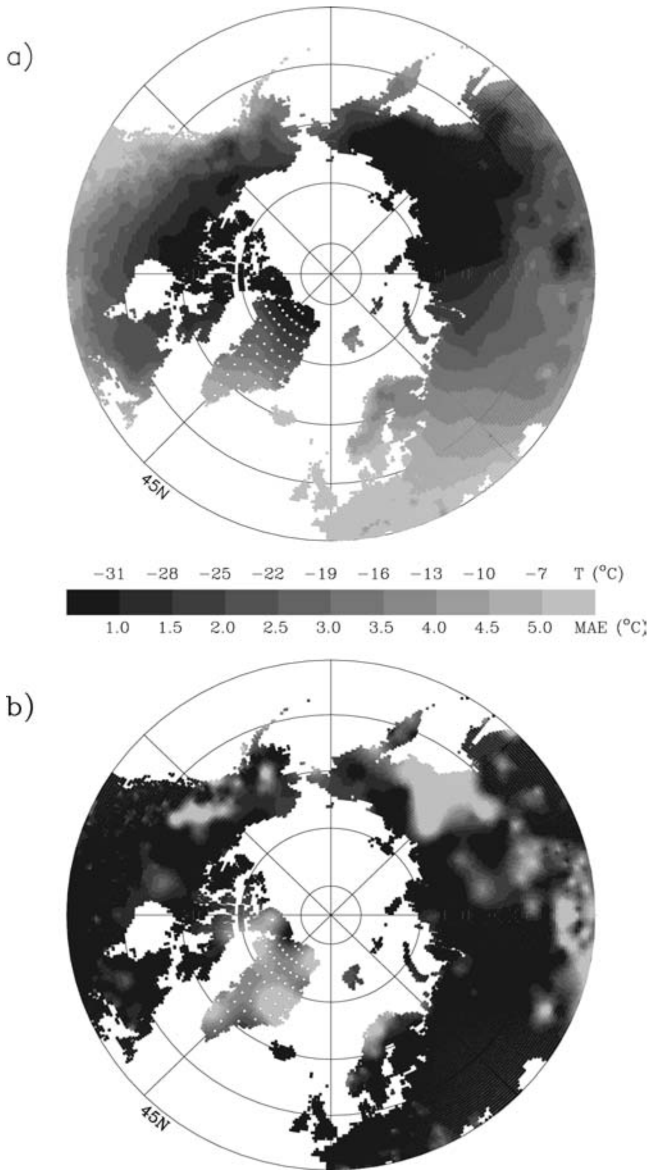

FIGURE 2. Traditionally interpolated winter average air temperature (a) and associated cross-validation MAE (b). The stippling over Greenland indicates that its grid-point values may be questionable and they are not used in computing terrestrial Arctic averages.

interpolation (Table 2). Winter air temperature averaged across the pan-Arctic basin is –24.84°C, 1.1°C colder than the estimate obtained from traditional interpolation.

Cross-validation errors for the DAI method (Fig. 3b) are considerably lower than those associated with traditional interpolation across the Alps and the high elevations along the coast of Norway. Errors are higher across the mountainous regions of central Asia and western Canada. Higher errors in such regions are likely due to variability in surface air-temperature lapse rates. It is interesting to note that DAI cross-validation errors are lower across the Alps, where meteorological stations are more numerous at higher elevations and therefore provide a better cross-validation check. Robeson and Janis (1998) found that DAI resolved a larger proportion of the spatial variability for annual and July fields but not for January fields, ostensibly because of lapse-rate variability. The spatially averaged DAI cross-validation error is 1.71°C, which is identical to the cross-validation error for the traditionally interpolated field (Table 2).

TABLE 2

Spatially integrated winter-average air temperatures over the terrestrial Arctic (north of 45°N) and Pan-Arctic drainage basin (neither includes Greenland), and associated cross-validation MAEs. Tabled values are from interpolations of winter-average air temperature station climatologies

	Traditional	DAI
Winter air temperature, north of 45°N	−18.25°C	−19.24°C
Cross-validation MAE, north of 45°N	1.71°C	1.71°C
Winter air temperature, pan-Arctic basin	−23.74°C	−24.84°C
Cross-validation MAE, pan-Arctic basin	1.86°C	1.96°C

Estimated surface air-temperature fields for each year in a time series can be useful in a number of applications such as climatic change analyses (Chapman and Walsh, 1993). In this paper, winter-average air temperatures were interpolated to the nodes of the 0.5° spherical grid for each year from 1961–1990. Traditional and DEM-assisted interpolation (DAI) procedures were applied and evaluated for all land areas north of 45°N (the terrestrial Arctic). Complicating the interpolations somewhat, the number of stations in each yearly network varied from 2146 stations in 1961 to a maximum of 2766 in 1975 (Fig. 5).

Traditionally interpolated yearly air-temperature fields (not shown) exhibit patterns similar to the climatologically averaged fields, with a strong west-to-east temperature gradient across Asia. The coldest winter temperatures occurred in northwestern Asia (Siberia), and a consistent north-to-south gradient was estimated over Greenland. During this 30-yr period, the coldest year was 1969 (–21.5°C) and the warmest was 1982 (–16.2°C).

Traditional interpolation cross-validation errors also were calculated at the stations from each yearly network, and cross-validation MAEs subsequently were interpolated to the grid. Patterns in the error fields are quite similar to patterns within the traditionally interpolated climatological air-temperature MAE field. The 30-yr average of the errors, for traditional interpolation, was 1.81°C, 0.1°C higher than the spatially integrated winter-average air-temperature MAE derived from the winter-average climatology (Table 2). This suggests that the climatology station network may better resolve the long-term air-temperature field than can the yearly networks.

Yearly winter-average air-temperature fields also were interpolated using DAI. The station networks from which these fields were constructed were identical to those used to estimate the traditionally interpolated time-series fields. DAI time-series estimates are comparable, in general pattern, to the traditionally interpolated fields. Within the period 1961–1990, the coldest year (based on DAI) was 1969 (–22.5°C) and the warmest was 1983 (–17.1°C).

Changes in winter-average surface air temperature are derived from the 30 yearly fields (described above). Trends were calculated at each 0.5° land grid node (45°N and poleward) using linear least-squares regression. Grid nodes over the oceans and Greenland are not considered. Analyzing the traditionally interpolated fields, warming is evident across much of western Canada, Alaska, and Asia (Fig. 6). The largest increases appear over western Canada ($>$0.1°C yr^{-1}) and central Asia, although the latter is due to a change in the station network rather than to warming. Most explained variances (r^2s) of the grid-point least-squares regressions (not shown), however, tend to be low ($<$0.1). Across western Canada some of the highest r^2s are found, but they range only from 0.2 to 0.4. Cooling appears over eastern Canada; across northeastern Asia; and over portions of Europe, Russia, and Scandinavia.

Our findings are broadly consistent with those of Chapman and Walsh (1993), who found increases in winter air temperatures from 0.10 to 0.15°C yr^{-1} across western Canada. They also reported cooling, –0.05 to –0.15°C yr^{-1}, over extreme northeastern Canada (and

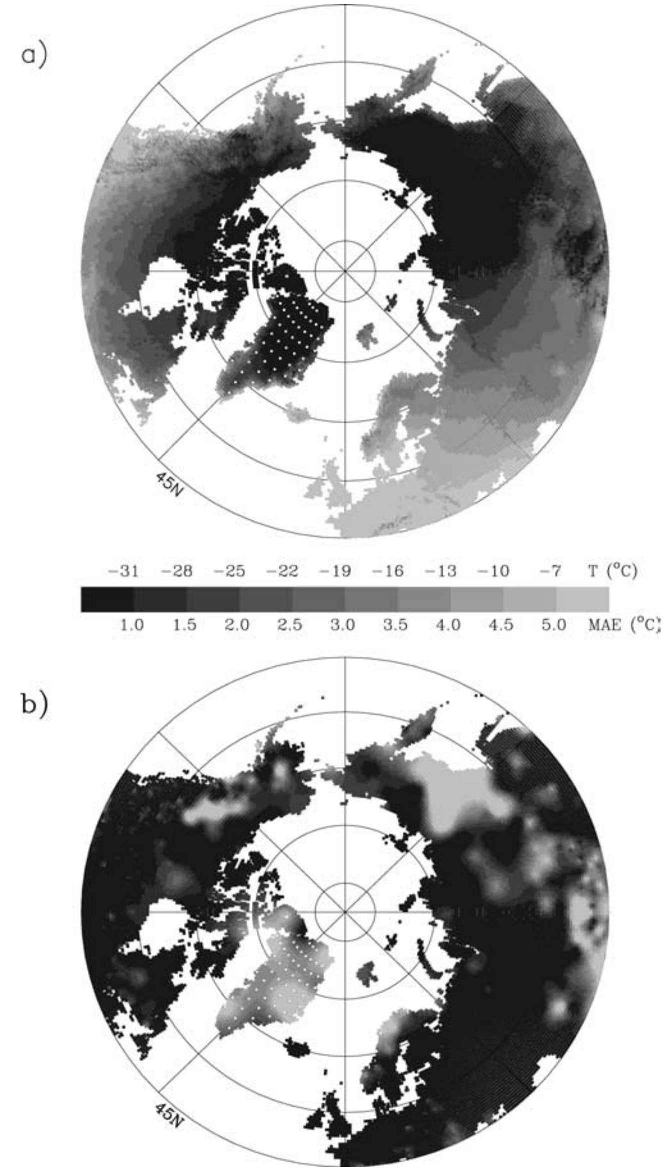

FIGURE 3. Winter average air temperature interpolated using DAI (a) and associated cross-validation MAE (b).

Greenland). Martin et al. (1997) similarly found warming over the Arctic, although the magnitude was considerably smaller (0.035°C yr^{-1}) and based on observations transmitted from drifting buoys in the Arctic Ocean.

Estimates of trends obtained from the DAI fields (Fig. 7) are similar to those derived from the traditionally interpolated fields, although the increases over western Canada are larger by as much as 0.1°C yr^{-1}. DAI-based warming is smaller in both magnitude and extent across central Asia. Explained variances (r^2s) associated with the DAI-based trends are nearly identical to those associated with the traditional-interpolation-based trends.

Increases in 20th century Arctic air temperature have been documented from the historical weather-station record. Warming has not occurred over the entire terrestrial Arctic, suggesting shifts in large-scale circulation patterns. It is possible, for example, that the warming may be related to decadal-scale changes in atmospheric circulation (Przybylak, 2000) or oceanic dynamics. Volodin and Galin (1999) also recently linked observed air-temperature trends (from 1977 through 1994) to increases in sea-surface temperature and low-stratosphere ozone depletion. In addition to changing atmospheric trace-gas concen-

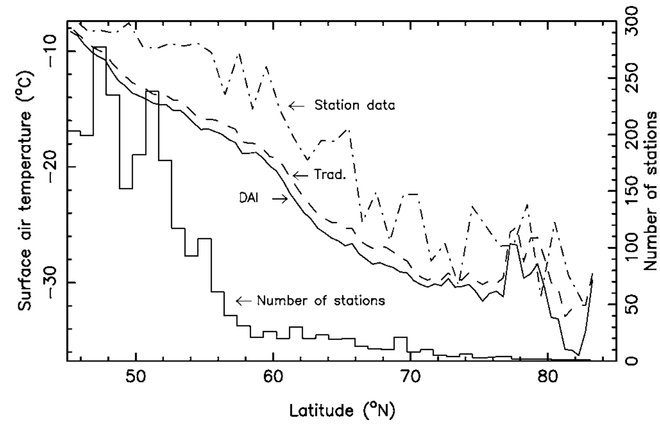

FIGURE 4. Latitudinally averaged winter average air temperature associated with the station records, traditional interpolation, and DAI. Latitude bands are at 0.5 increments for the gridded fields and 1 increments for the station data (Greenland is not included). The right-hand axis scales the number of stations within the 1 of latitude bands, beginning at 45°N.

trations and circulation patterns, land-surface modifications also may be a factor (Epperson et al., 1995).

Arctic-wide surface air-temperature trends can be analyzed further through the use of summary statistics and box plots. Based on yearly (winter) means at the weather stations (excluding Greenland), an average warming of 0.034°C yr^{-1} (over the 30-yr period) is apparent (Table 3, Fig. 8). This is 1.02°C over the entire 30 yr. Trends in the station means, however, may be biased by the uneven distribution of stations. To evaluate the spatially averaged trends across the entire Arctic land area (excluding Greenland), interpolated winter temperatures at the 0.5° grid were examined.

Analysis of the yearly, traditionally interpolated air-temperature fields (Fig. 9) reveals an increase of 0.049°C yr^{-1} in the Arctic mean air temperature as well as considerable interannual variability. Differences between the yearly distribution of traditionally interpolated winter air temperatures (Fig. 9) and the distribution of winter temperatures at the meteorological stations (Fig. 8) are marked. Indeed, the 30-yr mean of the winter average air temperatures at the weather stations is –9.04°C, whereas the 30-yr area-weighted mean of the traditionally interpolated grids is –18.20°C. This indicates an Arctic-wide warm bias in the weather-station network of more than 9°C. Approximately 75% of the interpolated air temperatures are below –10°C, and in most years, 95%

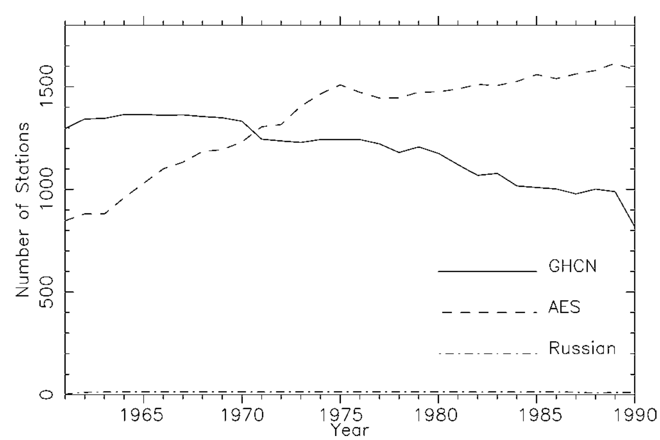

FIGURE 5. Number of stations used in 1961–1990 winter air temperature interpolations, from GHCV v2, AES Canada, and Russian data sets.

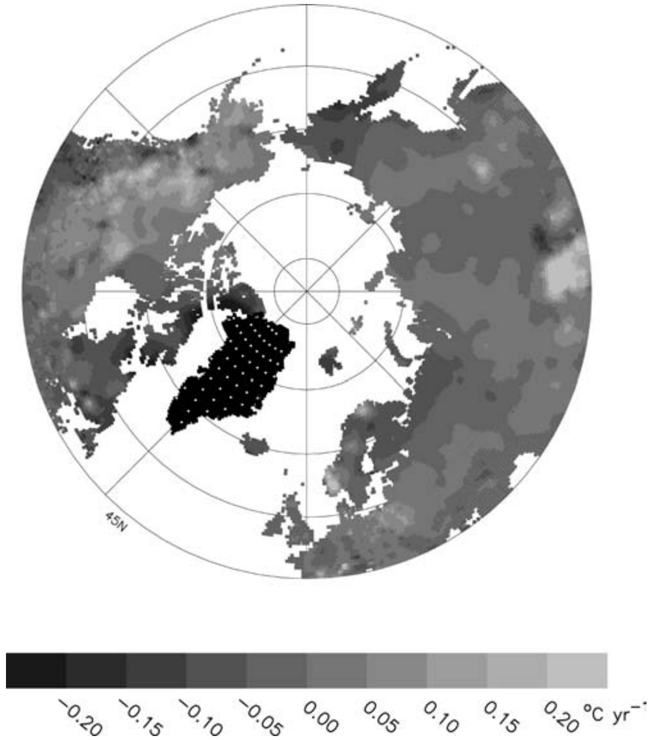

FIGURE 6. Winter average air-temperature trends based on traditionally interpolated yearly winter air-temperature fields.

of the gridded winter air temperatures are below freezing. Spatially averaged yearly MAEs (cross-validation errors) vary between 1.70 and 1.90°C (Fig. 9).

Evaluating the DAI-produced fields revealed similar trends and patterns, although all DAI-based winter-average air-temperature fields were slightly cooler (Fig. 10). The DAI-based air temperature trend

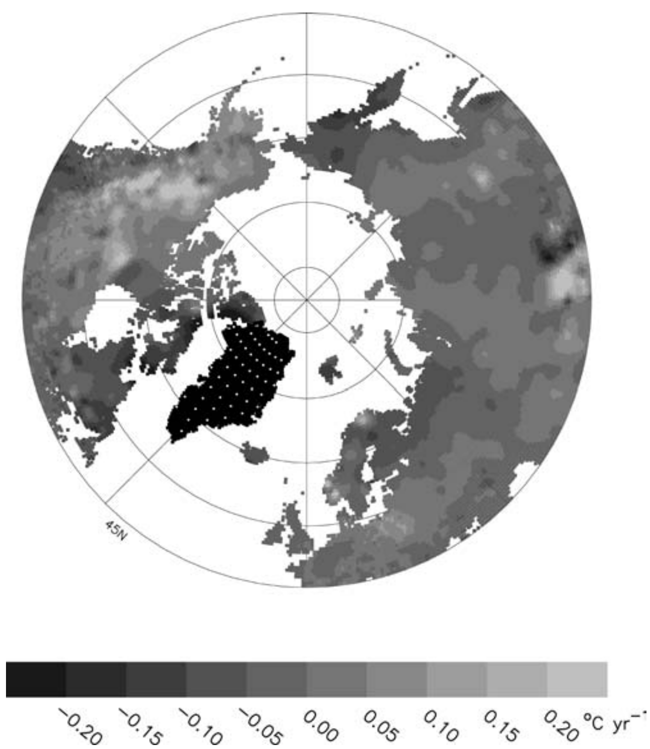

FIGURE 7. Winter average air temperature trends based on yearly DAI fields.

TABLE 3

Pan-Arctic average, winter air temperature increase alternately estimated from meteorological station data (no interpolation), the yearly traditionally interpolated air temperature fields, and the yearly DAI air-temperature fields

Interpolation method	Trend
Meteorological stations (no interpolation)	0.034°C yr^{-1}
Traditional interpolation	0.049°C yr^{-1}
DAI	0.048°C yr^{-1}

is 0.048°C yr^{-1} (Table 3), and the spatially averaged cross-validation errors (MAEs) are only slightly larger than those derived from traditional interpolation. Including the influences of elevation—especially the higher elevations that are undersampled by the weather-station networks—gives cooler estimates of winter air temperature.

Estimating Arctic-wide, winter warming from the gridded temperatures—following traditional interpolation or DAI (as opposed to the station temperatures)—marginally increases the warming. This suggests that the warming is being detected in regions that are underrepresented by the station network; in turn, the exact magnitude and spatial extent of the warming are somewhat uncertain. Specific areas within the terrestrial Arctic show considerable warming (Fig. 6 and 7), but the spatially averaged Arctic winter-average air temperature increases are much smaller.

Conclusions

Monthly mean surface air-temperature records from 4984 stations were analyzed to estimate Arctic winter air temperature north of 45°N over the period 1961–1990. Two spatial interpolation procedures were employed to estimate the monthly air-temperature fields from which 30-yr trends could be assessed. "Traditional" interpolation was used, as was DEM-assisted interpolation (DAI) (Willmott and Matsuura, 1995). Not surprisingly, the coldest winter average air temperatures were found across northeastern Russia and Greenland. A clear east-to-west air-temperature gradient across Asia also was apparent.

Interpolation of the long-term winter climatologies with DAI showed colder estimates over elevated regions such as the Rocky

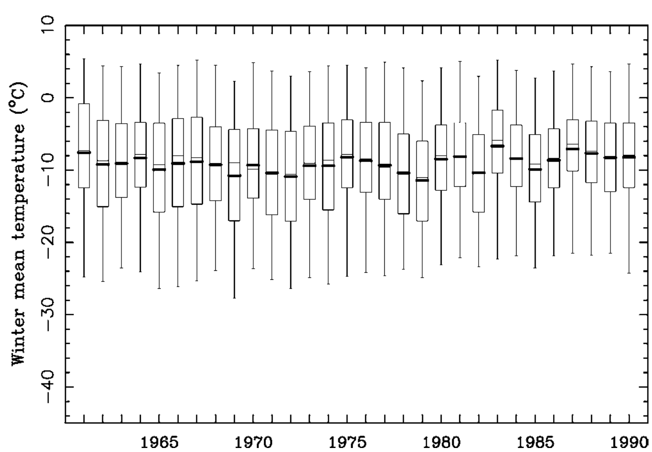

FIGURE 8. Yearly box plots of winter average air temperature as observed at the weather stations (excluding Greenland stations) from 1961 through 1990. The top and bottom of each box are the 25th and 75th percentiles, respectively. Boxplot whiskers represent the 5th and 95th percentiles. The spatial mean is the thick line and the median is the thin line.

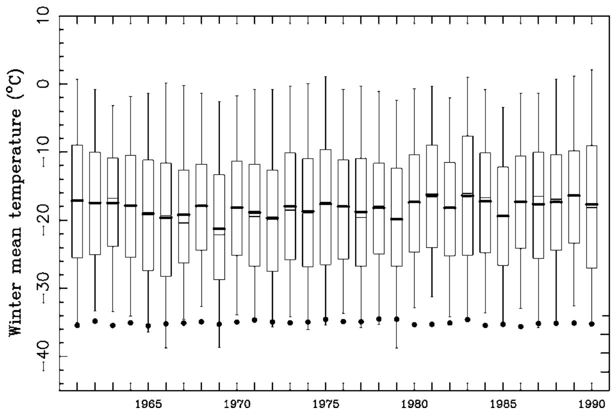

FIGURE 9. Yearly box plots of traditionally interpolated (gridded) winter average air temperature at all land grid nodes (excluding Greenland) from 1961 through 1990. The right axis scales the spatially averaged cross-validation MAE, indicated with solid circles.

Mountains, Greenland, and east-central Asia. When averaged across latitudinal bands, DAI grid nodes were colder than the traditional estimates—because stations tend to be located in the lower, warmer elevations—and both interpolated fields were colder than the raw meteorological station data. Thirty-yr means of the meteorological station temperatures, traditionally interpolated fields, and DAI fields were –9.04, –18.20, and –18.90°C, respectively. This clearly illustrates the importance of estimating Arctic mean temperatures from interpolated, gridded fields rather than from the station temperatures themselves.

Regression analyses of the gridded fields revealed considerable winter warming across western Canada and over areas within central Asia. A cooling trend also was evident across much of eastern North America. Explained variances associated with the trends, however, were generally low, owing to the considerable interannual variability in winter air temperatures. Traditional interpolation and DAI methods produced an Arctic-wide warming trend of 0.049 and 0.048°C yr^{-1}, respectively. At the weather stations (no interpolation), an average warming in Arctic mean winter air temperature of 0.034°C yr^{-1} was observed.

Spatially averaged cross-validation errors associated with the interpolated fields were between 1.7C and 2.0°C for the terrestrial Arctic and Arctic drainage basin grids. Adding more representative lapse rates to DAI may improve it.

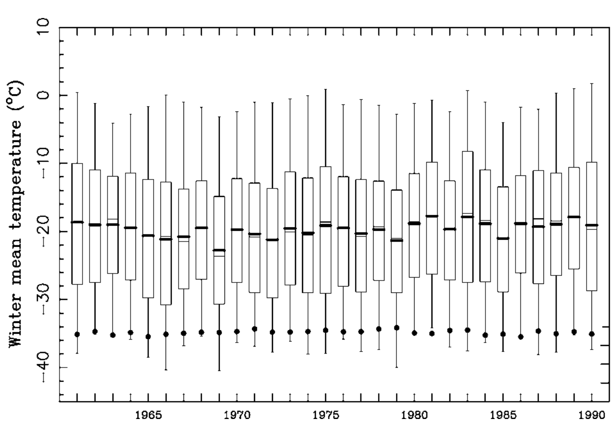

FIGURE 10. Yearly box plots of DAI (gridded) winter average air temperature at all land grid nodes (excluding Greenland) from 1961 through 1990. The right axis scales the spatially averaged cross-validation MAE, indicated with solid circles.

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