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VERTICAL STRUCTURE OF RECENT ARCTIC WARMING FROM OBSERVED DATA AND REANALYSIS PRODUCTS

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ABSTRACT

Spatiotemporal patterns of recent (1979–2008) air temperature trends are evaluated using three reanalysis datasets and radiosonde data. Our analysis demonstrates large discrepancies between the reanalysis datasets, possibly due to differences in the data assimilation procedures as well as sparseness and inhomogeneity of high-latitude observations. We test the robustness of Arctic tropospheric warming based on the ERA-40 dataset. ERA-40 Arctic atmosphere temperatures tend to be closer to the observed ones in terms of root mean square error compare to other reanalysis products used in the article. However, changes in the ERA-40 data assimilation procedure produce unphysical jumps in atmospheric temperatures, which may be the likely reason for the elevated tropospheric warming trend in 1979-2002. NCEP/NCAR Reanalysis show that the near-surface upward temperature trend over the same period is greater than the tropospheric trend, which is consistent with direct radiosonde observations and inconsistent with ERA-40 results. A change of sign in the winter temperature trend from negative to positive in the late 1980s is documented in the upper troposphere/lower stratosphere with a maximum over the Canadian Arctic, based on radiosonde data. This change from cooling to warming tendency is associated with weakening of the stratospheric polar vortex and shift of its center toward the Siberian coast and possibly can be explained by the changes in the dynamics of the Arctic Oscillation. This temporal pattern is consistent with multi-decadal variations of key Arctic climate parameters like, for example, surface air temperature and oceanic freshwater content. Elucidating the mechanisms behind these changes will be critical to understanding the complex nature of high-latitude variability and its impact on global climate change.

Keywords: Arctic warming, polar amplification, stratosphere

1. INTRODUCTION

The vertical structure of the Arctic atmosphere is shaped by a strongly negative surface radiation balance and poleward heat and moisture advection in the troposphere. On average, the Arctic north of 70 °N lacks about 100 W/m^2 in the radiation heat balance, resulting from the difference between the incoming and outgoing solar radiation at the top of the atmosphere (Nakamura and Oort, 1988). The heat balance is maintained through meridional heat transport from lower latitudes, which varies between 85 W/m^2 in the summer and 111 W/m^2 in autumn according to Nakamura and Oort (1988) and between 85 and 121 W/m^2 according to Overland and Turet (1994). The vertical structure of this heat advection controls mean atmospheric lapse rate and therefore the vertical heat exchange processes that define the fraction of heat used to warm the near-surface atmospheric layers. In the summertime, the bulk of heat advected to the Arctic is spent on heating the surface. In wintertime, the advected heat can substantially warm the Arctic atmosphere as has been suggested by radiative models (e.g., Overland and Guest 1992).

Vertical turbulent exchange in the Arctic atmosphere is generally weak. A very common and well-known feature of the Arctic atmosphere, especially during the cold season, is the frequent occurrence of near-surface air temperature inversions (Sverdrup, 1933). The surface temperature does not correlate well with the tropospheric temperature during strong inversion events because the super-stable boundary layer is decoupled from the tropospheric circulation (Tjernstroem, 2005). Surface Heat Budget of the Arctic Ocean (SHEBA) data show more frequent occurrence of cold than warm events in the surface temperature record (Uttal et al., 2002). This skewing of temperature behavior in the boundary layer is not well simulated by general circulation models (Beesly et al., 2000; Rinke et al., 2006; Byrkjedal et al., 2008). Weak sensitivity of boundary layer temperature to tropospheric advection could be one reason for biases in reanalysis data and model simulations during the cold season (Beesly et al., 2000; Tjernstroem et al., 2005; Rinke et al., 2006).

Understanding changes in the atmospheric lapse rate resulting from differential temperature trends at different heights is important for understanding the nature of tendencies in the Arctic environment. Indeed, the recent documented surface changes have been substantial (Serezze et al., 2000; Serreze and Francis, 2006; Francis and Hunter, 2007); the recent surface temperature trend in the Arctic is about twice as large as the Northern Hemisphere trend (IPCC, 2007). In the 1950s and 1960s, however, the temperature trends were negative and opposite to the global temperature trends (Polyakov et al., 2003; Johannessen at al., 2004). The spatial pattern of the Arctic surface air temperature (SAT) trends is also very heterogeneous; moreover, the trends from different data sources are not necessarily coherent (Kuzmina et al., 2008).

The atmospheric temperature in the Arctic exhibits large natural variability on a wide range of time scales from synoptic to multi-decadal (e.g., Overpeck et al. 1997; Polyakov et al. 2003; Bengtsson et al. 2004a). Available instrumental temperature records (particularly from the free atmosphere) are not of a sufficiently long duration to enable us to resolve slow processes. This is one reason for poor understanding of the mechanisms behind variability in the Arctic. There are, however, indications that the pattern of Arctic warming is partially controlled by the Arctic Oscillation (AO) and North-Atlantic Oscillation (NAO) (Thompson and Wallace, 1998).

It has been demonstrated that the stratospheric circulation in the Polar Regions is closely linked to surface conditions. For example, the Eurasian snow cover extent in October controls, to some degree, the AO/NAO behavior during the following winter (Cohen and Entekhabi, 1999; Cohen and Barlow, 2005; Cohen and Fletcher, 2007). The polar stratosphere responds to varying surface conditions, as in the example above; in addition, it can also be a driver of surface changes. For example, changes in the stratospheric circulation in the Southern Hemisphere due to declining ozone concentrations (Marshall et al., 2004) could be one explanation for the increase of sea-ice extent near Antarctica (Gillett et al., 2008). Various mechanisms for observed climate changes in the two hemispheres have been discussed in Gillett et al. (2008) and Turner et al. (2007); the important role of the stratospheric circulation is stressed. Understanding the reasons underlying changes in the Arctic atmosphere is therefore important as it is a crucial component of the tightly-coupled Arctic climate system.

It has been argued that the surface warming in the Arctic should be preceded by an elevated atmospheric warming induced by lateral heat transport (Flannery, 1984; Schneider et al., 1997; Alexeev, 2003; Rodgers et al., 2003; Alexeev et al., 2005; Langen and Alexeev, 2005; Langen and Alexeev, 2007). Using the European Re-analysis Agency (ERA)-40 data, Graversen et al. (2008) found such an elevated warming in the winter and summer temperature trends. This elevated warming has been questioned (Bitz and Fu, 2008; Grant et al., 2008; Thorne, 2008) and shown to be most likely a result of changes in the ERA-40 data assimilation system. Detailed analysis of spatiotemporal patterns of Arctic warming (including the reported elevated 1979–2002 warming in the Arctic troposphere) is one of the purposes of the article.

The plan of the article is the following. In section 2 we describe the data used for the study. In section 3 we study temperature trends for the 1979–2002 period from different reanalysis products. In sections 4 and 5 we test the robustness of the elevated ERA-40 warming against radiosonde data and other reanalysis products. The sensitivity of trends to changes in the time interval will be investigated. In section 6 we analyze the most recent (post-1990) temperature trends in the Arctic, in an attempt to diagnose possible reasons for those changes and to see if any of the station data support the elevated warming reported in ERA-40. This section is followed by the discussion and conclusions.

2. DATA

2.1. METEOROLOGICAL STATIONS AND REANALYSIS PRODUCTS

There is a variety of long-term data sources available for the Arctic atmosphere. A reasonable network of Arctic coast and island stations provides routine land-based meteorological observations. Measurements made from Russian patrol ships (Kuzmina et al., 2008) represent another source of data. A vast array of data from meteorological stations is available at the National Snow and Ice Data Center (NSIDC) web site (http://www.nsidc.org). An increasingly large number of satellite data products for the Arctic atmosphere have become available since the beginning of the satellite era in the 1970s.

However, no routine atmospheric observations were made over the Arctic Ocean before the beginning of the Russian North Pole drifting stations program in the mid-1930s

(Kahl, 1998). One to three of these stations were operating each year in the Arctic since 1950. This program was significantly downscaled in 1991. No radiosondes from the Russian North Pole drifting stations were launched after 1991 until 2007 (A.P.Makshtas, personal communication).

The North American Regional Reanalysis (NARR: Mesinger et al., 2006) represents an important source of data for various diagnostic and validation purposes. NARR uses a limited-area NCEP Eta model and data assimilation system. This model has high spatial and temporal resolution (32x45km in space and 3-hourly output in time). A wider variety of available data of different origin was assimilated, especially over the continental United States. The immediately available data covers the period from 1979 to 2005. We chose not to use NARR because the article is dealing with high Arctic and all the locations analyzed here are too close to the boundary of this reanalysis product.

The following datasets were used in this study.

29. IABP/POLES is the International Arctic Buoy Program (IABP) dataset (Rigor et al. 2000; Chen et al. 2002). The Polar Science Center of the Applied Physics Laboratory, University of Washington, in collaboration with IABP participants, has maintained a network of drifting Argos buoys in the Arctic Ocean since 1979. The dataset used in this study covers 1979–2004. The data were obtained from http://iabp.apl.washington.edu (Rigor et al., 2000; Chen et al., 2002).

30. IGRA dataset. For upper air profiles in our study we use data from the Integrated Global Radiosonde Archive (IGRA) dataset (Gaffen, 1996). This dataset contains most existing Arctic radiosonde data, including both a daily and monthly mean archive. The data coverage varies in time by region and country. Most observations start at the surface and go as high as 20 mb, especially in recent decades. The quality of radiosonde data is compromised by a variety of problems, including inhomogeneity of observations and processing problems (Gandin et al., 1988; Schwartz and Doswell, 1991; Gaffen, 1994). In general, quality assurance procedures for sounding data rely on principles of internal consistency, basic physical relationships, and/or statistical methods which are illuminated in Collins (2001) and literature cited therein. All the soundings are processed with quality controls (http://www.ncdc.noaa.gov/oa/climate/igra/index.php). A total of 113 IGRA stations are located north of 60 °N. Many stations in the Russian Arctic stopped launching radiosondes by the mid-1990s. A list of stations from IGRA used for this study and criteria for their selection are given below in section 2.3.

31. ERA-40 is the second-generation reanalysis dataset (Uppala et al., 2005). The ERA-40 assimilation procedure was significantly improved starting in about 1979 (Bengtsson et al., 2004a,b; Uppala et al., 2005). We use the 2.5×2.5 gridded ERA-40 dataset available from the European Center for Medium-range Weather Forecasts (ECMWF) website, which we find acceptable for the purposes of this study.

32. NCEP Reanalyses: We use both the older National Center for Environmental Protection (NCEP) reanalysis product (the so-called NCEP-1, Kalnay et al. (1996)) and the newer NCEP-Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP)-II Reanalysis (we will call it NCEP-2, for brevity), described in Kanamitsu et al. (2002). As noted in Kanamitsu et al. (2002), the newer product can be used "…as a supplement to the NCEP-National Center for Atmospheric Research (NCAR) reanalysis especially where the original analysis has problems. The differences between the two analyses also provide a measure of uncertainty in current analyses." Data from both

products are available to the present day, which makes them very useful for comparison with the observations.

33. JRA-25: The Japanese 25-year ReAnalysis (JRA-25) was conducted by the Japanese Meteorological Agency (JMA) in collaboration with the Central Research Institute of Electric Power Industry. The available dataset covers period from 1979–2004. The data assimilation was done using 3DVar. The global model's resolution used for the reanalysis was T106 (Onogi et al, 2007).

2.2. PROBLEMS WITH REANALYSIS DATA

Major data assimilation systems use a variety of data in one form or another. However, the data are not uniform in space and time. Discontinuities in observational systems can potentially impact the quality of reanalysis data. Bromwich and Wang (2005) argued, for example, that accuracy of reanalysis data may suffer over areas with sparse observations.

Bengtsson et al. (2004a,b) questioned the quality of trends computed from the ERA-40 reanalysis for the period 1958–2001 in the context of changes to the global observing system. The ERA-40 global mean temperature in the lower troposphere has a trend of +0.11 K dec^{-1} over the period of 1979–2001, which is slightly higher than the microwave sounding unit (MSU) measurements, but within the estimated error limit. For the period 1958–2001, however, the warming trend was larger (0.14 K dec^{-1}), but Bengtsson et al. (2004a,b) found this increase to be an artifact of changes in the observing system. When these corrections are introduced, the warming trend is reduced to 0.10 K per decade.

Simmons et al. (2004) compared monthly-mean anomalies in SAT from the ERA-40 and NCEP/NCAR reanalyses with corresponding values from the Climate Research Unit (CRU) dataset CRUTEM2v (Jones and Moberg, 2003). Least-square linear trends were found to be significantly lower for both reanalysis projects, but ERA-40 trends are within 10 % of CRU for the whole northern hemisphere when computed from 1979 onwards. There is, however, a warm model bias present at middle and high latitudes and a cold bias at low latitudes. The ECMWF model (the basis for ERA-40) produces a cold bias at mid- and high-troposphere in data-sparse regions. This feature may amplify the troposphere temperature trends in ERA-40 because the Arctic data coverage has varied between 1979 and 2002. Trends and variability in ERA-40 throughout the planetary boundary layer (1000 mb to 850 mb layer) are generally similar to those at the surface from the late 1970s onwards.

Bromwich and Wang (2005) pointed out that some of the ERA-40 tropospheric cold bias was introduced by the satellite instrument High-resolution Infra-Red Sounder (HIRS)-2 on the Television Infra-Red Observation Satellite (TIROS) Operational Vertical Sounder (TOVS). A quote from the ECMWF website (http://www.ecmwf.int/research/era/ERA-40/Data_Services/section3.html): " … A further problem of concern is cold bias in the lower troposphere (below ~500 mb) over ice-covered oceans in both the Arctic and the Antarctic. A related problem in Arctic precipitation has also been identified. These polar cold biases arise from the assimilation of HIRS radiances. Changes to the thinning, channel-selection and quality control of the infrared data that were introduced for analyses from 1997 onwards to reduce the tropical precipitation bias have also virtually eliminated the cold polar biases." TOVS satellite input to ERA-40 started in 1979 and was replaced by ATOVS in 1998. Its replacement corrected the negative tropospheric bias.

Trenberth et al. (2001a) showed that while the MSU and NCEP/NCAR reanalysis temperatures show fairly good agreement, large discrepancies with the ERA-40 temperatures indicate that changes in the satellite observing system may have adversely affected the ECMWF reanalyses, especially in the tropics. The temperature discrepancies have a complex vertical structure that is not fully understood. Changes in the observing system limit the applicability of the reanalysis products to some climate studies.

Despite the problems, Bromwich and Wang (2005) and Bromwich et al. (2007) find NCEP/NCAR and ERA-40 reanalysis reliable to some extent in the Arctic during the modern satellite era (post 1979). According to these studies, one of the most significant problems is treatment of clouds and the associated radiation budget, which produces excessively strong short-wave radiation over land and therefore surface temperatures that are too high.

For the discussion throughout this article, it is important to keep in mind that reanalysis products are essentially the result of sophisticated data interpolation procedures with dynamical constraints. In the areas scarcely covered by direct measurements of temperature, satellite information acquires relatively large weight so that any change in satellite instruments can have an implication for the quality of assimilated air temperature. Because of the possible strong decoupling between the surface and the free atmosphere, potential errors introduced at the surface or aloft sometimes cannot be corrected by the assimilation system. Vertical temperature profiles in the Arctic are almost never nearly adiabatic.

Table 1. Station list. Shaded areas represent approximate periods of data availability.

Stations	1950	1960	1970	1980	1990	2000	Location
Alert							82.5N 62.3W
Barrow							71.3N 156.8W
Bjornoya							74.5N 8.67W
Dikson							73.5N 80.4E
Eureka							80.0N 85.9W
Fairbanks							64.8N 147.9W
Jan Mayen							70.9N 8.67W
Resolute Bay							74.7N 94.9W
Thule							76.5N 68.7W
Tiksi							71.6N 128.8E

2.3. RADIOSONDE STATION DATA USED IN THIS STUDY

To test reanalyses data quality we selected ten Arctic stations with data coverage, some starting as early as the 1950s. We included stations with relatively good data coverage. Many Russian stations stopped launching radiosondes after the break-up of the Soviet Union in 1991, which explains why we did not include more stations from the Russian Arctic. Data coverage and station locations are listed in Table 1. Geographical locations are plotted in Figure 1 – the stations are spread all over the Arctic in a more or less uniform manner. We decided to keep Jan Mayen station since it is located above 70 ºN although it is often viewed as a North Atlantic rather than as an Arctic station.

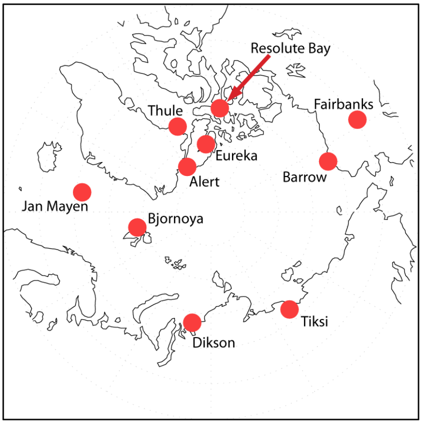

Figure 1. Stations used for the analysis

3. TEMPERATURE TRENDS FROM REANALYSIS DATASETS

Reanalysis datasets are used here in order to test the existence of the elevated high-latitude warming pattern found in ERA-40 (Graversen et al., 2008). We demonstrate that the two reanalysis datasets, ERA-40 and NCEP-1, show substantially different patterns of high Arctic warming during 1979–2002 for all four seasons (Figure 2). We used an algorithm described in Wigley (2006) for assessing trends and their significance (direct link to the description of the algorithm is found here: http://www.climatescience.gov/Library/sap/sap1-1/finalreport/sap1-1-final-appA.pdf).

The 1000 mb temperature trend in ERA-40 is lower approximately north of 70–80 ºN for all seasons except spring compared with that from NCEP-1. There is a pronounced maximum in ERA-40 temperature trend at 925 mb in the winter and at 700 mb in the summer. Autumn trends are dramatically different as well; ERA-40 does not show any maximum in trend near the surface, unlike the corresponding trend from NCEP/NCAR reanalysis. In all cases the largest trend maxima in ERA-40 temperatures are found in the area north of 80 ºN, corresponding to the Arctic Ocean. Note that no regular observations are available for that area.

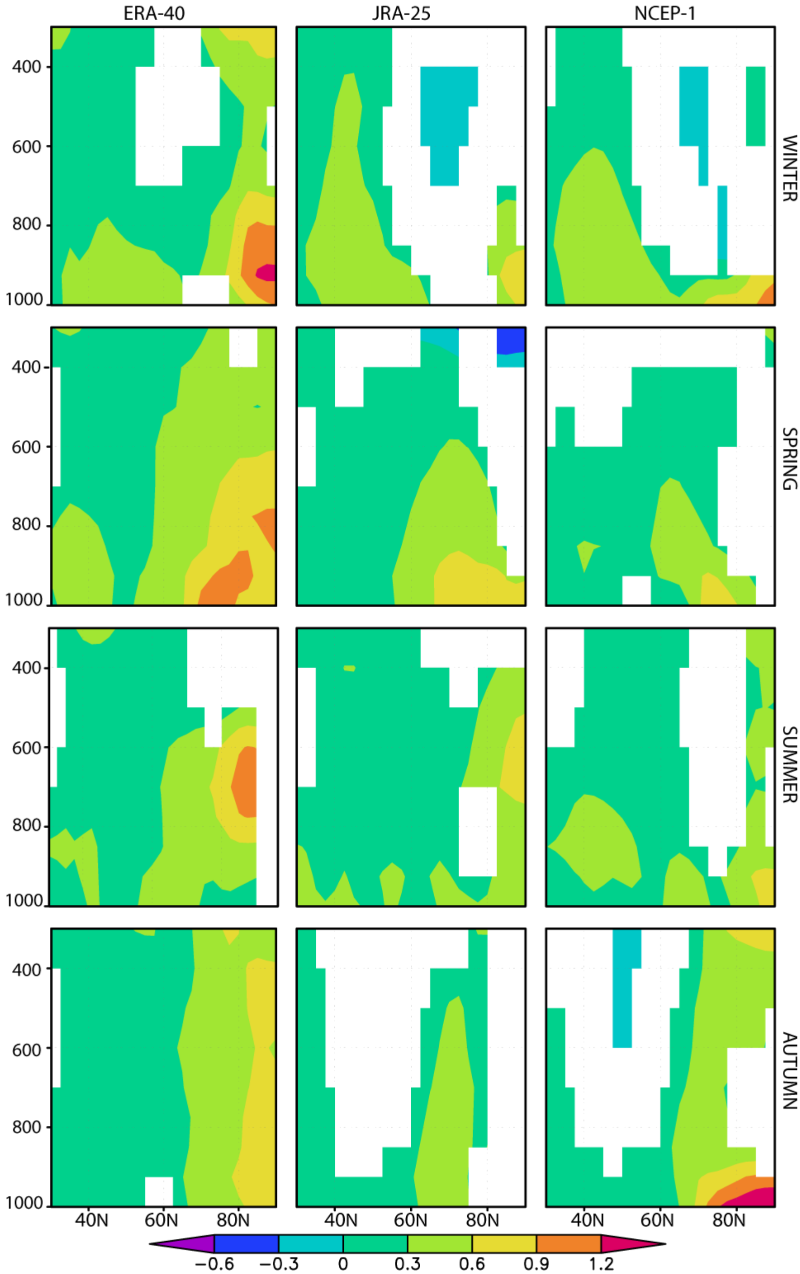

Figure 2. Linear trend of zonal mean air temperature (K/decade) as a function of height (mb) and latitude calculated over 1979–2001 period for four seasons; winter: 1st row, spring: 2nd row, summer: 3rd row, autumn: 4th row. Left column: ERA-40, center column: JRA-25; right column: NCEP-1. Only significant trends are shown.

Spatially averaged (70–90 °N) winter temperature difference between ERA-40 and NCEP-1 is shown in Figure 3a. Temperatures derived from these two datasets differ substantially at the end of the ERA-40 period, starting approximately after 1980 until 1998. Figure 3b and 3c show the same difference at two different levels: 925 mb and 600 mb, for ERA-40 and JRA-25.

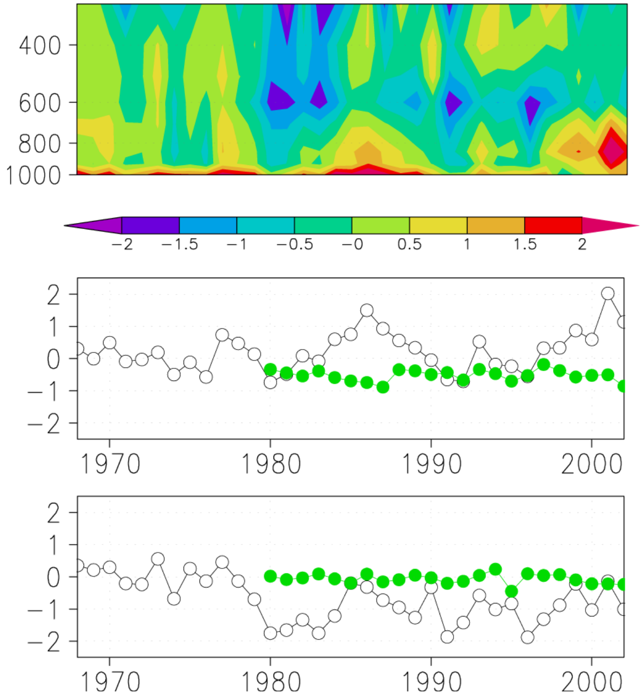

Figure 3. (a) Winter air temperature (degrees K) averaged over 70–90 °N, difference between ERA-40 and NCEP-1; (b) the same difference between ERA-40 and NCEP-1 at 925 mb (black open circles), JRA-25 and NCEP-1 (green circles); (c) – same as in (b), except for the values were plotted at 600 mb.

The horizontal structure of the trends from various datasets at different levels is shown in Figures 4 and 5. The summer trend in ERA-40 at 700 mb is significantly greater than the surface trend (Figure 4), while the ERA-40 winter trend has a maximum at 925 mb (Figure 5). These ERA-40-based elevated patterns of warming are among the major findings of Graversen et al. (2008). However, these two features are not present in trends calculated from other reanalysis products. NCEP-1, NCEP-2, and JRA-25 trends presented in Figures 4 and 5 do not show a stronger elevated warming in the winter or the summer. There is only one place where a weak elevated warming can be seen, which is in the NCEP-1 summer trend at 925 mb (central panel in Figure 4, 3rd row). Note a disagreement between the datasets even at the surface; e.g., much stronger winter warming in the Canadian Archipelago is seen in NCEP-1 than in the other datasets (Figure 5, column 1, row 3). The Beaufort and East Siberian seas are two other areas where reanalysis products disagree at the surface.

Geographically, the area of the biggest disagreement between tropospheric trends from ERA-40 and other datasets (NCEP-1, NCEP-2, or NARR) is located in the high Arctic. This disagreement could potentially be tested at several high-latitude stations. However, Ny Alesund lacks a sufficiently long radiosonde record. The Franz Joseph Land and Severnaya Zemlya stations stopped launching sondes in the early 1990s. Other stations in the Canadian Archipelago with long radiosonde records (e.g., Eureka, Thule) are located outside the area of interest. The only station close to the area of interest is Alert, where observations started as early as 1963 and have continued until present. We will test the robustness of reanalysis temperature trends against observations at Alert in the next section.

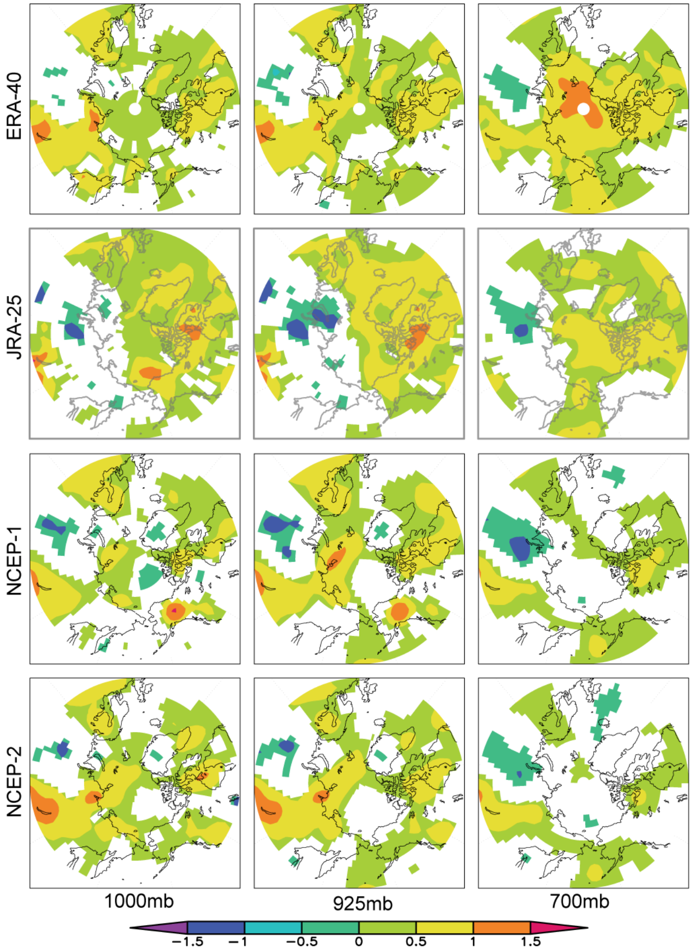

Figure 4. Summer temperature trends (1979–2002), K/decade for ERA-40, NCEP-1, NCEP-2, and JRA-25 at different pressure levels: 1000 mb, 925 mb, and 700 mb.

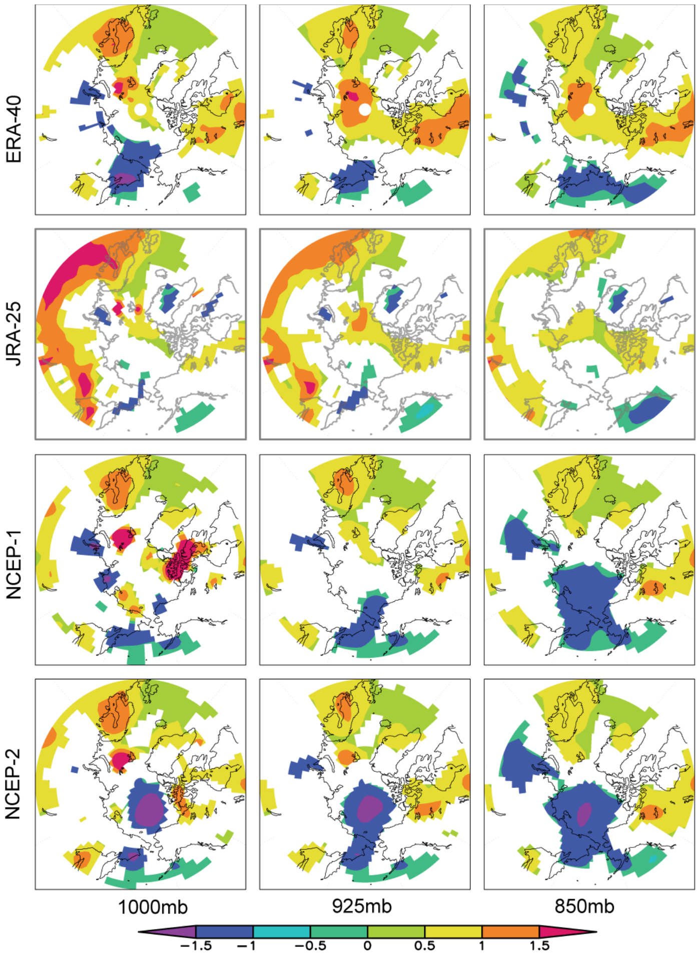

Figure 5. Winter temperature trends (1979–2002), K/decade for ERA-40, NCEP-1, NCEP-2, and JRA-25 at different pressure levels: 1000 mb, 925 mb, and 850 mb.

4. TEMPERATURE TRENDS FROM REANALYSIS AND RADIOSONDES AT ALERT STATION

Alert station is particularly suitable for assessment of reanalysis products due to its proximity to the high Arctic and its location in an area of persistent sea-ice cover that significantly reduces spatio-temporal inhomogeneities.

Because years after 1997 are identified as years with potential problems for the ERA-40 dataset, we test reanalysis products against Alert station data for two time windows. The first period covers 1979–2002, which represents our 'standard' ERA-40 period. The second period covers an earlier period of 1976–1997. Note that the two periods do not have the same time length. We chose the second period for two reasons. By ending it in 1997 we avoid problems related to changes in the ERA-40 data assimilation system, while by starting in 1976 we avoid problems associated with the abrupt changes in the Arctic that occurred around that time due to the shift in the Pacific Decadal Oscillation (PDO) index. The PDO index was predominantly negative before 1976. The associated changes in the large-scale circulation have been shown to affect many climate parameters in the Arctic (Mantua et al., 1997; Hartmann and Wendler, 2005). In particular, the SAT rend calculated for 1951–2001 in Fairbanks is positive. However, this overall positive trend is "…strongly based by the sudden shift in 1976 from the cooler regime to a warmer regime. When analyzing the total time period from 1951 to 2001, warming is observed; however, the 25-yr period trend analyses before 1976 (1951–57) and thereafter (1977–2001) both display cooling, with a few exceptions", according to Hartmann and Wendler (2005).

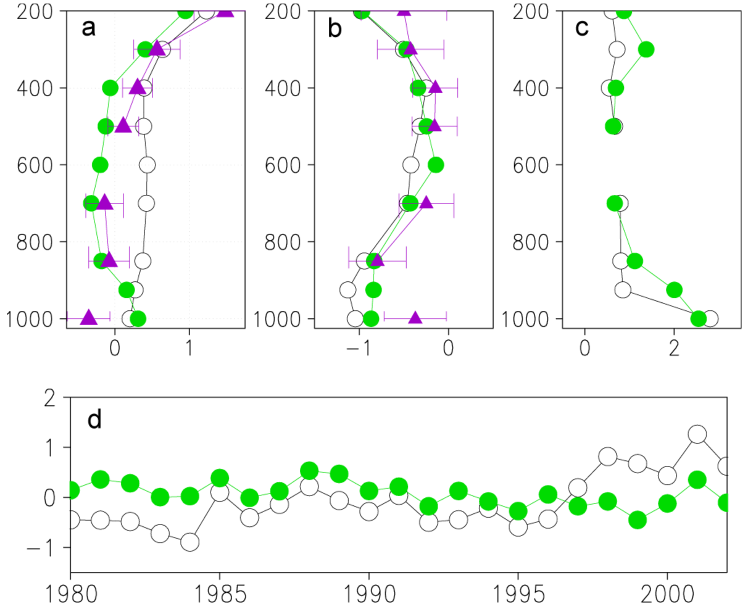

Figure 6. (a) Winter temperature trend at Alert for 1979–2002 (K/decade); (b) trend for 1976–1997; (c) RMS error calculated using monthly means for 1979–2002, all months (K): ERA-40, black circles; NCEP-1, green circles; radiosonde IGRA data, magenta triangles and significance estimate represented by one standard error. (d) Difference between ERA-40 and IGRA (black circles) and difference between NCEP-1 and IGRA (green circles) at 700 mb, degrees K.

Winter trends for the two periods derived from the two reanalysis products ERA-40 and NCEP-1 are shown in Figure 6. For the first period the vertical trend profiles show substantial differences; the NCEP-1 trend is the closest to the trend calculated using radiosonde data, while the ERA-40 trend overestimates the observed trend. A typical value for the standard error of the calculated trends at 700 mb is about 0.3–0.4 K decade^{-1}. However, for the second, earlier, period the trend profiles from the two reanalysis products are very similar and, more importantly, they are both much closer to the radiosonde trends. ERA-40 temperatures are colder before 1997 and a big jump occurs in 1998, which is the primary reason for the strong warming trend. This is also true for other seasons (not shown). Our analysis for spring, summer, and autumn showed that ERA-40 systematically overestimates lower- and mid-tropospheric trends for 1979–2002 while trends calculated for 1976–1997 for both ERA-40 and NCEP-1 are very close to IGRA radiosonde data. Unfortunately, NCEP-2 and NARR data are not available before 1979.

Based on this analysis, we argue that the significantly closer agreement between two reanalysis products for 1976–1997 compared to 1979–2002 suggests that ERA-40 temperature trends for the latter period might not be very robust and could therefore be considered as an artifact of changes in the data assimilation system. Therefore, trends derived from this product (ERA-40) should be treated with caution. However, the root mean square errors calculated using monthly mean temperatures for all months from January 1979 through September 2002 demonstrate that ERA-40 is generally better than NCEP-1 (Figure 6c) or, actually, all other reanalysis products used here (not shown) in terms of deviation from the observations. This indicates that ERA-40 better captures seasonal-scale variability in the Arctic; it better captures synoptic variability as well, as shown in Graversen et al. (2008).

5. LOWER STRATOSPHERIC TEMPERATURE TRENDS

This section is devoted to analysis of Arctic upper-tropospheric/lower-stratospheric temperature trends. We use NCEP-1 and radiosonde data wherever available to verify the reanalysis results. It is known (Ramaswamy et al., 2006; IPCC, 2007) that the global stratosphere has been cooling for the last couple of decades. However, Figure 6 shows that the temperature trend in the lower stratosphere at Alert changes its sign from cooling to warming when we shift the time window from 1976–1997 to 1979–2002. Here we present a closer look at this phenomenon, without explaining the physics behind this trend in much detail.

Shown in Figure 7 are the stations' radiosonde winter temperatures at 100 mb as a function of year and temperature trends as a function of height for periods before and after 1990. There is a visible, prolonged minimum in the temperature at 100 mb in the late 1980s–early 1990s. This temperature minimum explains our choice for the break point between the two analysis periods. The right panels show that at most stations the temperature trends at around 100 mb reversed significantly from one period to the next, with the strongest change observed at the stations located in the Canadian Arctic: Alert, Eureka, Resolute Bay, and Thule. Figure 1 from Ramaswamy et al. (2006) also shows a similar result.

A possible mechanism for those trends would be a change in the atmospheric circulation. The lower most panel of Figure 7 shows air temperature variations at 100 mb in Tiksi along with 'AO-like' index. We calculated EOFs of seasonal mean sea level pressure fields (December–January–March) and used the first EOF's principal component (PC) as our 'AO' index. The spatial structure of this EOF is very similar to the conventional Thompson, Wallace (1998) picture of AO (not shown here). Indeed, the overall strength of the polar vortex at 100 mb height weakened after 2000 compared to that prior to 1980, and the center of the vortex shifted toward the Siberian Arctic (Figure 8). This shift resulted in the position of the temperature minimum moving towards Siberia, and in pronounced warming over the Canadian Arctic. The isolines of the 100 mb geopotential height serve as a good proxy for the streamfunction of the flow. The weakening of vortex strength also resulted in the overall warming of the lower stratosphere almost everywhere throughout the Arctic. These changes of the 100 mb temperature trend from cooling before 1990 to warming after 1990 are also seen in the radiosonde IGRA data (Figure 8e, f) for various locations in the Arctic.

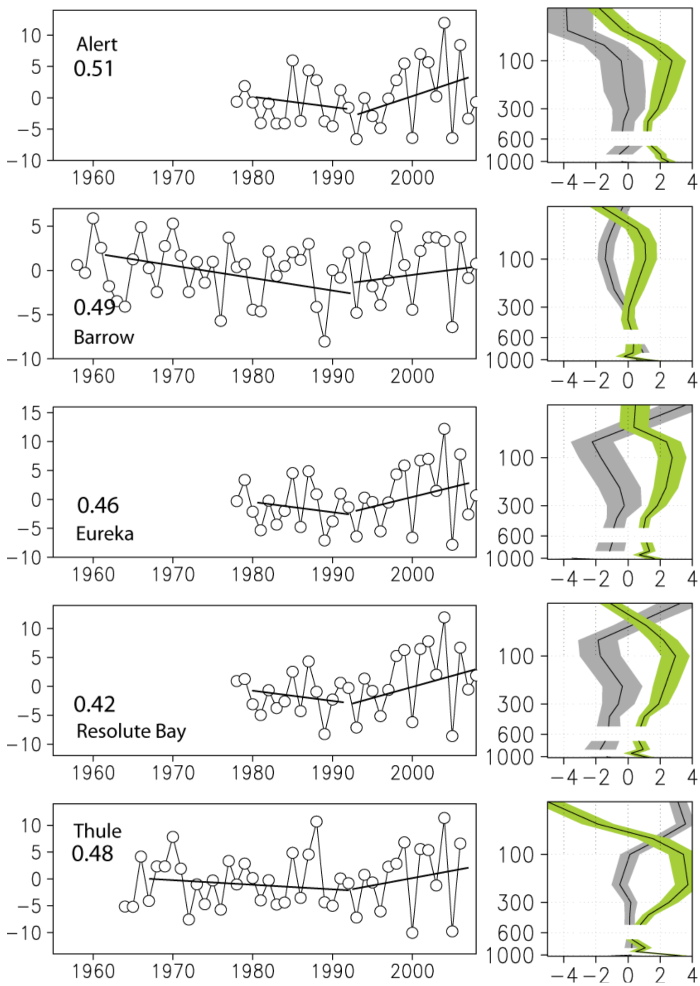

Figure 7. (Left) Temperature anomalies for different stations at 100 mb; straight lines show approximate trends before and after 1990. (Right) Temperature trends (black thin lines) as a function of height with error estimates for the same stations calculated for the period before 1990 (grey shaded area) and from 1990 to 2008 (green shaded area). Green circles in the lower right panel show the principal component of the first EOF of the sea level pressure (multiplied by 3 to match the scale) calculated using seasonal means (DJF) for 1949–2008. Values near each station's names indicate correlation of air temperatures with this principal component.

Figure 9(a, b) shows first EOFs of 100 mb seasonal mean geopotential height and air temperature. It can be easily seen that the structure and location of changes in the geopotential height and air temperature shown in Figure 8 are very similar to the EOFs of the corresponding fields. On top of that, their principal components highly correlate to our 'AO-like' index (Figure 9c). The geopotential height- and air temperature's PCs correlation coefficient is 0.92. The geopotential height's- and 'AO' PCs correlate at 0.71. The air temperature and AO correlate at 0.56. Therefore we conclude that most of the variability and long-term changes observed at our station can be explained by the dynamics of the Arctic Oscillation.

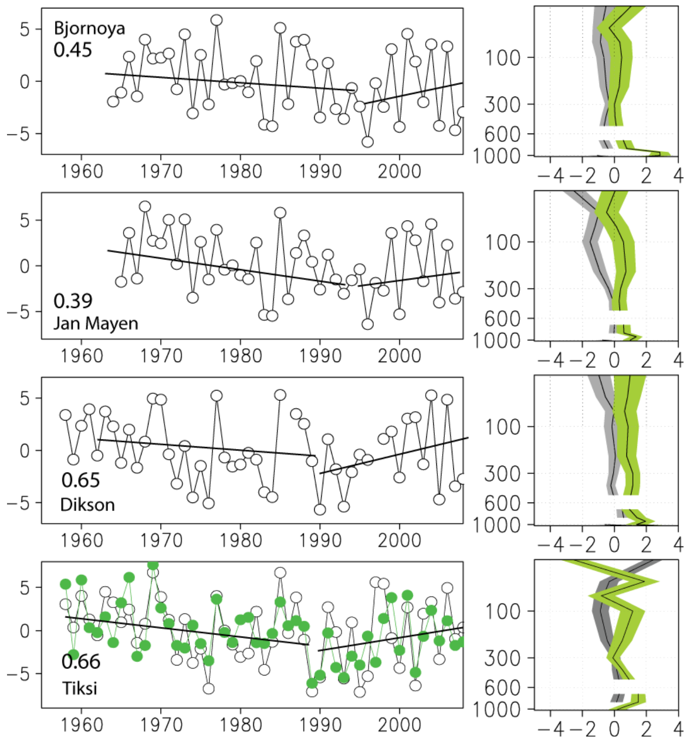

Figure 7. Continued

6. STRUCTURE OF TRENDS SINCE 1990

6.1. SURFACE TRENDS

We now estimate robustness of the most recent trends in the Arctic atmosphere from NCEP-1, NCEP-2, and IABP/POLES. As mentioned earlier, there is some disagreement between these datasets. For example, Figure 6 shows that both NCEP and ERA-40 root mean square errors have a big maximum at the surface for Alert station. The near-surface (1000 mb) 1979–2002 winter temperature trends in the Beaufort Sea are unexpectedly negative according to NCEP-2 and positive according to NCEP-1. Also, the reanalysis datasets disagree on the magnitude of the trends. This motivated us to compare NCEP products with IABP/POLES data for the period of 1990–2004. The choice of the shorter time period is explained by the availability of the IABP/POLES data. For the sake of simplicity we chose to omit the JRA-25 SAT trends, because as we will see from the following the dataset demonstrate substantial disagreement so that adding one more product will not change this result.

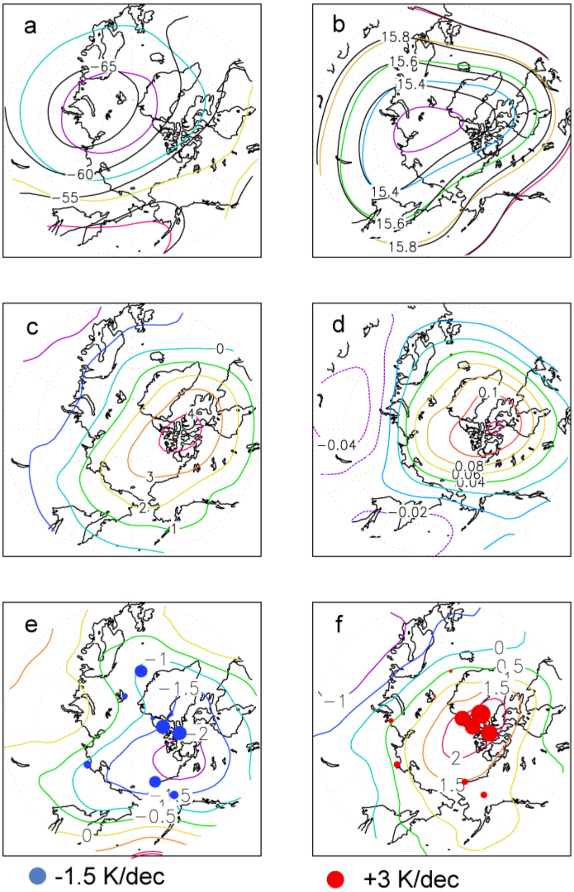

Figure 8. (a) Winter air temperature at 100 mb (degrees C) calculated from NCEP-1 for 1980–90 (color contour lines) and 2000–2008 (black lines); (b) Geopotential height at 100 mb (km) calculated for 1980–90 (color contour lines) and 2000–2008 (black lines); (c) Difference between winter air temperatures (degrees C) at 100 mb calculated for 2000–2008 minus 1980–1990; (d) Same as in (c), except for geopotential height (km); (e) Winter air temperature trend at 100 mb (degrees K/decade) before 1990; (f) Same as in (e), except for trend after 1990.

Figure 10 shows the SAT trend from two reanalysis products, NCEP-1 and NCEP-2, and the IABP/POLES dataset. The three sources of data provide a generally consistent picture for all seasons, although geographically the differences are quite substantial. A pattern of winter warming (Figure 10, upper row) is captured by all three datasets, with a positive warming trend located on the American side of the Arctic and a slightly negative trend on the Siberian side. The maximum differences are located in the Beaufort, Chukchi, and East Siberian seas. There are disagreements in the Canadian Arctic, not only on the magnitude of the trends, but also on the positions of the maxima. Areas of warming are more widespread in NCEP-1 and IABP/POLES datasets in all seasons compared to NCEP-2. NCEP-2 trends (Figures 5 and 10) have more areas with negative temperature changes than NCEP-1, ERA-40 and IABP/POLES temperature trends.

One of the centers of disagreement is in the Beaufort Sea. Comparison of SAT trends for the Beaufort Sea limited to 170 ºW–130 ºW, 72 ºN–81 ºN from NCEP and IABP/POLES datasets shows that NCEP-1 overestimates the rate of warming (Figure 11). NCEP-2 and NARR tend to produce warmer SATs for the time period around 1990 and then to converge with IABP/POLES data towards 2004, which results in negative trends for both, contradicting the trend from the IABP/POLES dataset. The IABP/POLES winter trend averaged over the Beaufort Sea is positive, although it is weaker than the NCEP-1 trend; this results from a stronger negative bias in NCEP-1 SAT compared to IABP/POLES data. One interesting observation from Figure 11 can be made: all datasets show wider spread during 1980–90th compared to the latest decade, which could be an indicator of improving data coverage in the area.

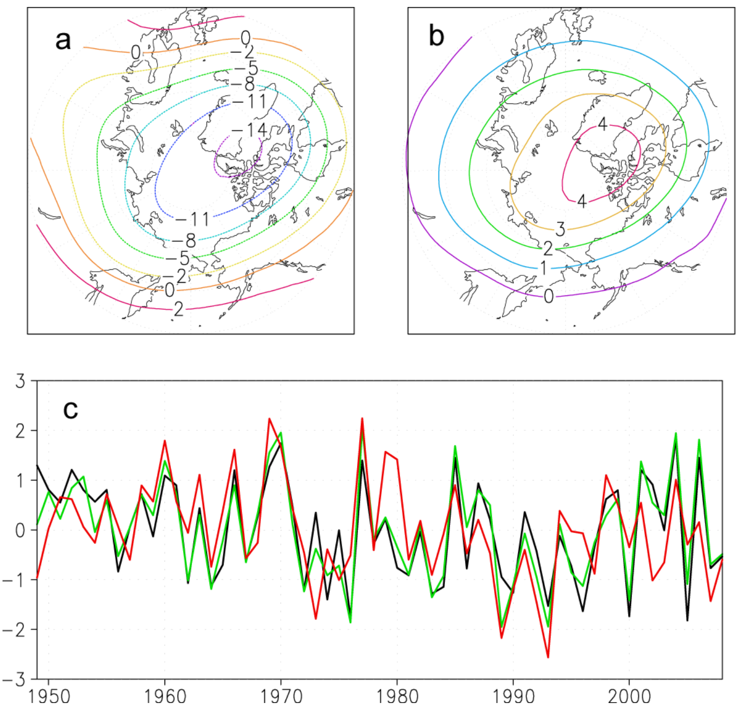

Figure 9. (a) First EOF of NCEP-1 air temperature at 100 mb calculated using seasonal means (DJF) over the 1949–2008 period; (b) same as in (a) except for the 100 mb height; (c) – principal components of the 1st EOF of the air temperature from (a), black line; geopotential height at 100 mb from (b), green line and of the 1st EOF of the sea level pressure, red line, calculated similarly using seasonal means. Correlation coefficients between the principal components are given in the text.

6.2. LOWER STRATOSPHERIC WARMING

The reported earlier winter warming trend in the lower stratosphere (Figure 6) is confirmed by data from most of the stations used in our analysis (Figure 12). It is most pronounced in the Canadian Arctic (Alert, Eureka, Resolute Bay, Thule) with values reaching as high as 5K/decade at Alert. The Russian Arctic (Dikson, Tiksi) and the North Atlantic (Bjornoya, Jan Mayen) show significant positive winter temperature trends as well. Fairbanks and Barrow station data show a weak lower tropospheric warming trend in the spring and no warming signal in the winter. The lower stratospheric warming trend extends into the spring at some of the stations (Alert, Eureka, Resolute Bay, Dikson, Tiksi); this could be explained by the same mechanism associated with the change in the lower stratospheric circulation.

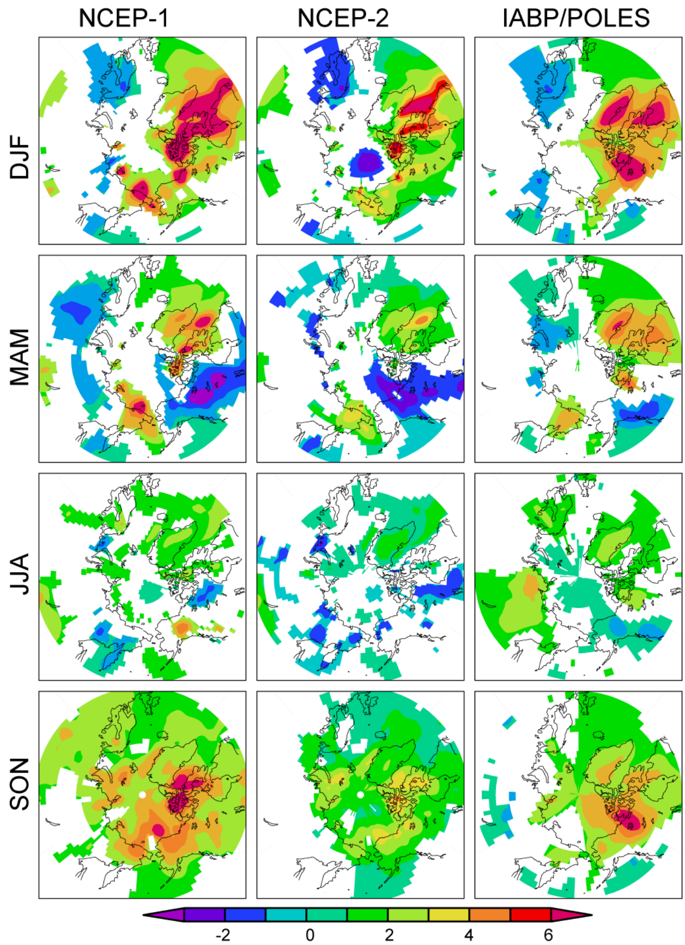

Figure 10. Temperature trends at 2 meters for different datasets and seasons (K/decade) calculated for 1990–2004. Only areas with significant trends are plotted.

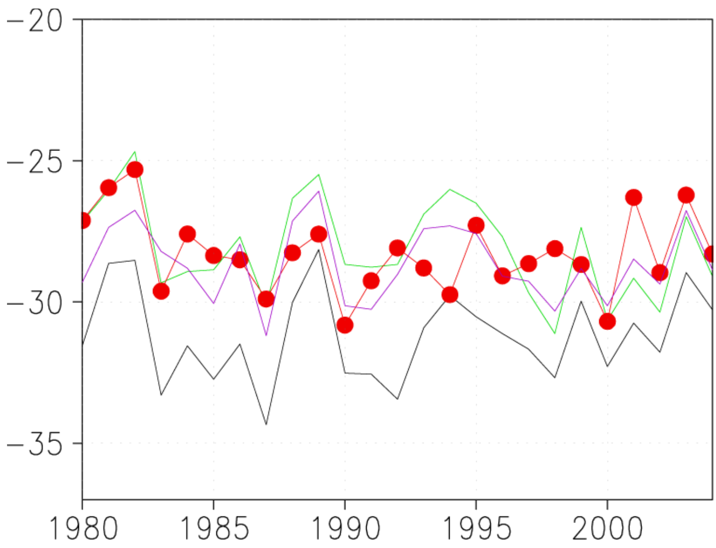

Figure 11. Winter surface air temperature (degrees C) averaged over the Beaufort Sea (170 °W–130 °W, 72 °N–81°N) using NCEP-1 (black line), NCEP-2 (green line), JRA-25 (purple line), and IABP/POLES data (red line with circles).

The warming has been accelerating since 1990; therefore it would be natural to look for faster elevated warming in the latest data, assuming that this air is coming from warmer lower latitudes. However, the only station showing faster elevated warming in the lower troposphere is Tiksi in the winter; Tiksi data also show some hints of faster warming in the summer (Figure 12). The NCEP-2 results (not shown here) are similar to the NCEP-1-based results. Note that the NCEP-calculated trends are in a reasonable agreement with the station data for all seasons (Figure 12).

7. DISCUSSION AND CONCLUSIONS

Recent temperature increases in the Arctic are larger than elsewhere. This is a matter of great concern due to the impact the rising temperatures can have on the Arctic and global climate systems. The importance of the consequences brings about hot debates concerning the spatio-temporal structure of the changes in the Arctic and the mechanisms driving these changes. One of the main topics of the debate is whether the Arctic warming is primarily local in nature, or is induced by changes in global circulation patterns.

Robustness of the recently-reported elevated tropospheric warming trend found in ERA-40 in the Arctic (Graversen et al., 2008) was tested using NCEP/NCAR reanalysis and NARR datasets as well as the radiosonde data archive IGRA. This trend has been questioned in a number of studies. Thorne (2008) compared ERA-40 with the zonal mean radiosonde-based HadAT2 (Thorne et al., 2005) dataset and satellite retrievals and concluded that lack of observations could be the primary reason for non-robustness of ERA-40 trends poleward of 80 °N. Grant et al. (2008) compared ERA-40 trends with trends calculated from a subset of Arctic radiosonde data and came to a similar conclusion. Using the HadCRUtv3 dataset and satellite data, Bitz and Fu (2008) showed that the Arctic mid- and lower troposphere winter warming in ERA-40 has been greatly overestimated. Serreze et al. (2009) came to a similar conclusion about surface-based polar amplification using the NCEP/NCAR reanalysis dataset and JRA-25.

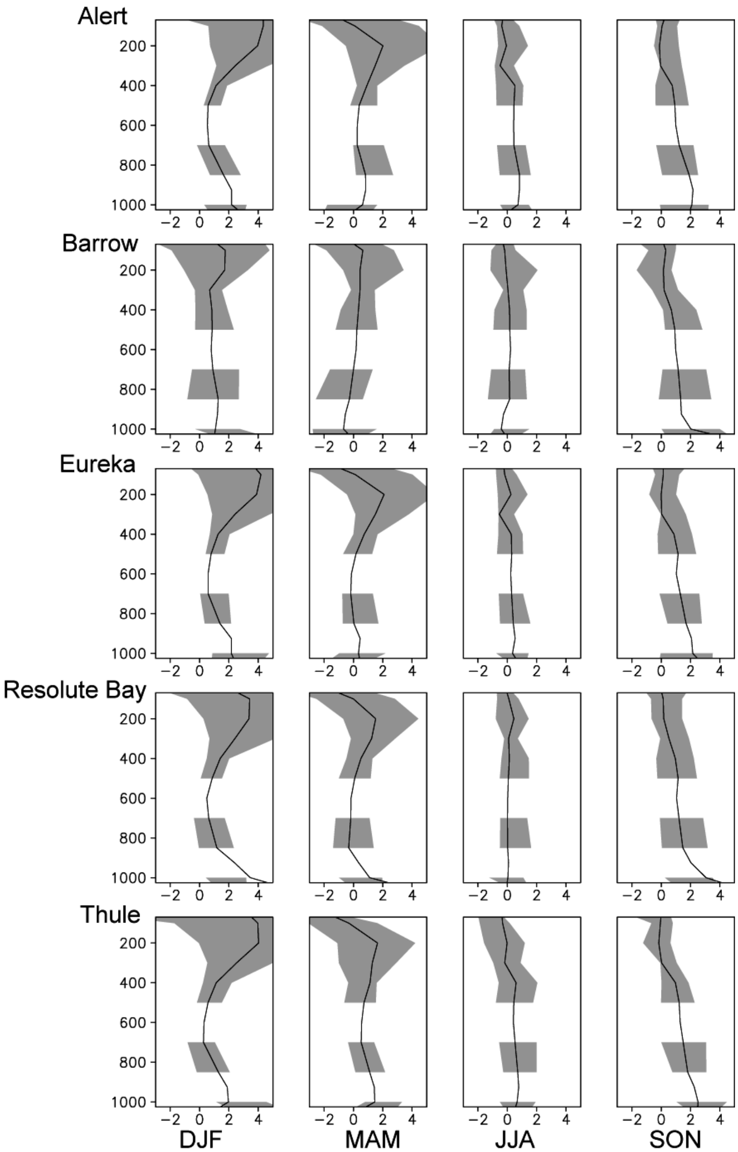

Figure 12. Temperature trends throughout the year at different stations (K/decade) for 1991–2008. NCEP-2: black thin line; radiosonde IGRA data: shaded area having width of two standard errors, centered around the trend (not shown).

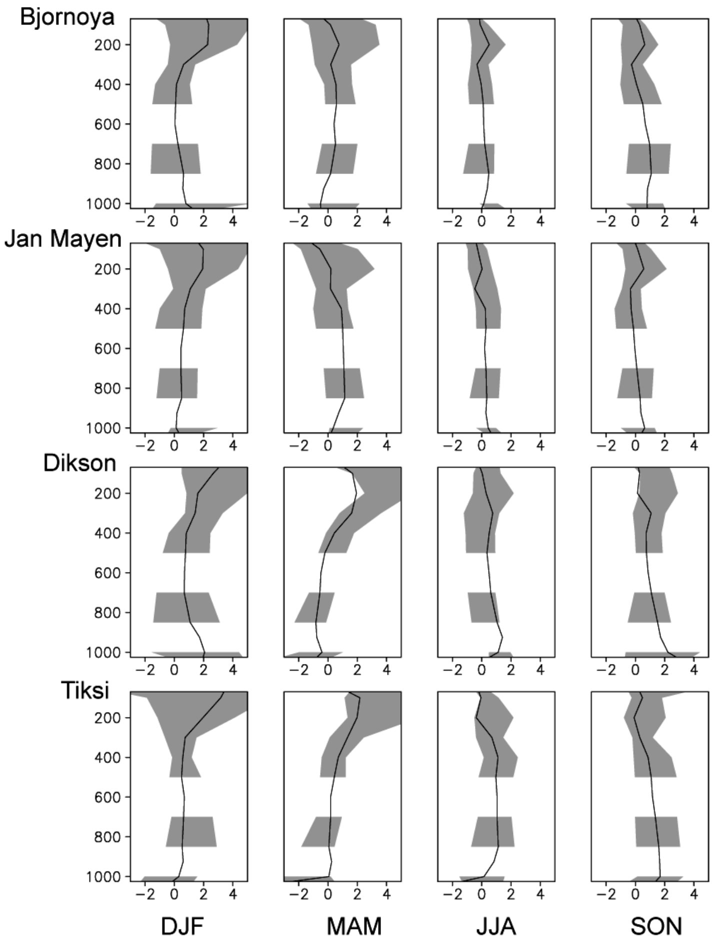

Figure 12. Continued

This study tests the robustness of the reported ERA-40 trends based on other reanalysis products (NCEP-1, NCEP-2, and NARR) and detailed analysis of radiosonde data from one particular station (Alert). Our analysis suggests that the ERA-40 elevated warming trend calculated for 1979–2002 could be an artifact of changes in the data assimilation system. According to the ECMWF documentation, 1997–98 were problem years for ERA-40 because a change in the satellite input resulted in a cold tropospheric bias before 1998. Our analysis of ERA-40 data indicates that in 1998 the temperature in the lower troposphere experienced an unphysical jump. Faster elevated warming in the atmosphere is not confirmed by other reanalysis products, or by the radiosonde dataset IGRA. The Arctic warming accelerated even more after 2002; therefore, we extended our analysis to 2007. However, the most recent trends (for 1990–2007) do not exhibit a pattern of faster elevated warming in the lower or middle troposphere. Instead, we found that significant changes are occurring in the lower stratosphere.

Main results of this study can be formulated as follows:

1. Reanalysis products disagree with each other over trends for 1979–2002. ERA-40 shows faster elevated warming in the central Arctic, unlike any of the NCEP/NCAR or NARR products. NCEP/NCAR and NARR trends tend to be in better agreement with trends calculated from the radiosonde IGRA dataset than trends calculated from ERA-40, especially in the free atmosphere. ERA-40 shows a consistently warmer trend in the low- and mid-troposphere.
2. The extent of disagreement between trends depends on the time period chosen for the analysis. During the earlier period (1976–1997) the disagreement between trends derived from reanalysis products and the IGRA dataset is smaller, which indicates that the last few years of the ERA-40 data period are contaminated by a spurious trend in the temperature, which is not found in other products. This jump in the temperature around 1997 has been discussed in Bromwich and Wang (2002) and documented on the ECMWF website (http://www.ecmwf.int) and has been identified as due to the change in satellite instrument from HIRS to ATOVS.
3. The uncertainty in temperature trends is too great to make any conclusive statements about the faster elevated warming in the lower troposphere in the Arctic during the last two decades. However, the only station showing elevated warming similar to what has been described by Graversen et al. (2008) is Tiksi. All nine other stations used in our analysis do not show any indication of faster elevated warming in the troposphere in any season.
4. Disagreement in temperature trends between the datasets used for the analysis is substantial even at the surface. All the "hotspots" of disagreement are in regions with sparse data coverage. There is a major disagreement between reanalysis products and IABP with regards to the trend at the surface for 1990–2004. The recent winter warming signal over the Beaufort Sea is statistically significant according to IABP/POLES and NCEP-1. However, other reanalysis products disagree substantially over trend magnitude and even sign: NCEP-2 results show a significant negative SAT trend over the Beaufort Sea.
5. Our analysis of radiosonde data from the IGRA dataset revealed a change in the temperature trend in the lower stratosphere (200 mb to 70mb) around 1990 when the trend changed its sign from negative to positive. This signal is robust to a varying degree throughout the array of available stations in the Arctic with sufficiently long temperature records. This lower stratospheric warming signal is most pronounced in the Canadian Arctic.
6. This pattern of temporal changes may be associated with multi-decadal fluctuations on time scales of 50–80 years, which are known to be exceptionally strong in the Arctic and North Atlantic. Polyakov et al. (2008) demonstrated a strikingly coherent pattern of long-term variations of the key Arctic climate parameters and strong coupling of long-term changes in the Arctic climate system with those at lower latitudes. Remarkably coherent low-frequency variations are expressed by the Arctic SAT, Arctic Ocean fresh water content and intermediate Atlantic Water core temperature, fast-ice thickness, and North Atlantic sea surface temperature. For example, associated with this variability, the Arctic SAT record shows two warmer periods in the 1930–40s and in recent decades, and two colder periods early in the 20th century and in the 1960–70s. The observed stratospheric air temperature variations are consistent with this pattern. The long-term changes in the upper troposphere/lower stratosphere seem to occur together with changes at the surface, including the extent of Eurasian snow cover and sea ice. Elucidating the mechanisms behind these relationships

will be critical to our understanding of the complex nature of low-frequency variability found in the Arctic and at lower latitudes, and its impact on climate change.

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