Do Changes in the Midlatitude Circulation Have Any Impact on the Arctic Surface Air Temperature Trend?

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ABSTRACT

The warming of the near-surface air in the Arctic region has been larger than the global mean surface warming. There is general agreement that the Arctic amplification of the surface air temperature (SAT) trend to a considerable extent is due to local effects such as the retreat of sea ice, especially during the summer months, and earlier melting of snow in the spring season. There is no doubt that these processes are important causes of the Arctic SAT trend. It is less clear, however, whether the trend may also be related to recent changes in the atmospheric midlatitude circulation. This question is the focus of the present paper.

Model experiments have shown that in a warmer climate responding to, for example, a doubling of CO₂, the atmospheric northward energy transport (ANET) will increase and cause polar SAT amplification. In the present study, the development of the ANET across 60°N and its linkage to the Arctic SAT have been explored using the ERA-40 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF). It is found that during 1979–2001, the ANET has experienced an overall positive but weak trend, which was largest during the period from the mid-1980s to the mid-1990s. In addition, it is found that the Arctic SAT is sensitive to variability of the ANET across 60°N and hence to variability of the midlatitude circulation: A large ANET is followed by warming of the Arctic where ANET leads by about 5 days. The warming is located primarily north of the Atlantic and Pacific sectors, indicating that baroclinic weather systems developing around the Icelandic and Aleutian lows are important for the energy transport. Furthermore, it is suggested here that a small, but statistically significant, part of the mean Arctic SAT trend is linked to the trend in the ANET.

Another important indicator of the midlatitude circulation is the Arctic Oscillation (AO). Through the 1980s and early 1990s the AO index has shown a positive trend. However, even though a part of the SAT trend can be related to the AO in localized parts of the Arctic area, the mean Arctic SAT trend shows no significant linkage to the AO.

1. Introduction

During the last decades, the Arctic region has experienced significant climate changes (ACIA 2004). These include a smaller sea ice extent especially in the summer season (e.g., Chapman and Walsh 1993; Parkinson et al. 1999; Deser et al. 2000), earlier continental spring melting of snow (Robinson et al. 1995), thawing of permafrost (e.g., Osterkamp and Romanovsky 1999; Oberman and Mazhitova 2001), melting of glaciers (Dowdeswell et al. 1997), an increased melting zone of the Greenland ice sheet (Abdalati and Steffen 2001; Steffen et al. 2004), enhanced precipitation (Serreze and Hurst 2000), and an increase of the mean surface air temperature (SAT), which is about twice as large as the global mean increase (e.g., Chapman and Walsh 1993; Rigor et al. 2000). As a consequence of these alarming signs, the climate in the Arctic region has attracted considerable scientific attention in recent years.

Special attention has been drawn to the Arctic amplification of the SAT trend. It is believed that the amplification is due to local feedback mechanisms such as those associated with the trends in ice and snow cover. Negative trends of these quantities lead to a reduction of the surface albedo. Furthermore, as a consequence of the insulating effects of ice, the negative trend in sea ice cover is believed to have resulted in an increased transport of heat from the ocean to the atmosphere (e.g., Deser et al. 2000). In the summer season, the
Arctic sea ice volume has decreased by 40% relative to the situation prevalent from the 1940s through the 1970s (Rothrock et al. 1999). Rigor et al. (2002) report that, in both the summer and winter season, changes of the wind stress might have given rise to larger areas with thin ice and leads in the eastern part of the Arctic Ocean that, in turn, possibly have contributed to the observed warming there. In the winter season, the changes of the wind stress are related to changes of the Arctic Oscillation (AO), and Rigor et al. (2002) find that a strong winter AO causes thinning of the sea ice in the eastern Arctic Ocean in winter, associated with thinner ice than usual in spring, more open water in summer, and increased freezing in autumn. The result is an increased transport of heat from the ocean to the atmosphere during the rest of the year following a winter with strong AO conditions. A linkage between the Arctic sea ice and the AO is also documented by Deser et al. (2000), and Kwok (2000) has reported changes in the Arctic sea ice motion associated with an increase in the AO-related North Atlantic Oscillation (NAO). Dickson et al. (2000) have shown that the positive trend in the NAO has given rise to stronger and warmer inflow of Atlantic water to the Arctic region that, in turn, also might have added to the Arctic warming.

In addition, the unique boundary layer conditions at high latitudes have also presumably influenced the Arctic SAT trend. Since strong surface inversions are a dominating feature of the Arctic temperature profiles during the winter season (Persson et al. 2002), a modest input of heat at the surface in winter results in a large increase of the SAT. This is in contrast to, for example, the Tropics, where heat input is distributed vertically throughout the troposphere by deep convection.

However, mechanisms causing damping of the Arctic SAT trend relative to the global mean have also been proposed. Chase et al. (2002) and Tsukernik et al. (2004) suggest that, in the winter season, the Arctic SATs are indirectly linked to the sea surface temperatures (SSTs) of the open water areas. The winter SSTs in the Arctic are about −2°C, which by moist adiabatic convection processes implies temperatures at 500 hPa at about −45°C. This is close to the observed 500-hPa winter temperature in more or less the entire Arctic region. It is assumed, in turn, that for Arctic winter conditions, outgoing IR radiation at the surface is balanced by downward emission from the troposphere, which links the tropospheric temperatures to the surface temperatures. Hence, since SSTs are expected to experience only small changes in the winter season under global warming conditions, the same holds for the Arctic tropospheric temperatures and, as a consequence, the Arctic SAT.

Polyakov et al. (2002) have investigated centuurylong records of temperature, ice extent, and ice thickness. They suggest that the polar amplification of the SAT trend could be explained just in terms of natural variability.

The atmospheric circulation in the midlatitudes has changed during the last decades, particularly in the winter season (Lu et al. 2004, and references therein). This is to some extent captured by the AO (e.g., Thompson et al. 2000) and the related NAO (e.g., Hurrell 1995). An alternative indicator of the circulation is the atmospheric northward energy transport (ANET). A comprehensive discussions of this quantity was provided by Oort and Peixóto (1983) and Peixóto and Oort (1983), who estimated the transports from rawinsonde data. This work constitutes the foundation of a well-known book dealing with the general circulation of the atmosphere and ocean (Peixóto and Oort 1992). A later study by Trenberth and Stepaniak (2003) presents recalculations of the transports using data based on the more modern reanalysis technique. Attempts to document the full energy budget of the polar regions have also been made despite the lack of data in these regions, which makes it especially difficult to estimate the surface fluxes. Such an attempt was undertaken by Nakamura and Oort (1988) and followed up by Overland and Turet (1994).

In the present study, the ANET across 60°N has been estimated using ERA-40 reanalyses data (Uppala et al. 2005) from the European Centre for Medium-Range Weather Forecasts (ECMWF). It is found that the ANET across 60°N has an overall positive trend during the period from 1979 to 2001. This is also true for the AO index, but where the ANET shows an upward trend through the first half of the 1990s to a level that is maintained during the second half of the decade, the AO shows high values in the beginning followed by a negative tendency at the end of the 1990s. In addition, it is found from regression of the Arctic SAT on the ANET that the variability of the former quantity is sensitive to the variability of the later. It is suggested that the positive trend in the ANET explains a small, but statistically significant, part of the Arctic SAT trend in recent decades.

The AO, which is the leading mode of variability of the Northern Hemisphere (NH) sea level pressure (SLP) field (Thompson and Wallace 1998), captures some large-scale dynamical properties of the atmosphere in the NH midlatitudes (Thompson and Wallace 2000, 2001). The AO shows a dipole structure between the polar region and the midlatitudes with the largest meridional difference in the Atlantic sector. The temporal evolution of the AO is given by what is known as
the AO index, where large values are associated with a stronger-than-usual zonal flow in the midlatitudes ad- 
vecting warm air over the continents, implying warmer 
than usual winter condition there.

Through the 1980s and early 1990s the AO index has 
shown positive tendencies. This has raised the question: 
Is there a linear linkage between the trends of the NH 
SAT and the AO index? Several studies show such a 
relation (e.g., Thompson et al. 2000; Moritz et al. 2002; 
Wu and Straus 2004). It has also been proposed that the 
AO trend may be anthropogenically induced (Shindell 
et al. 1999; Fyfe et al. 1999). However, in recent years 
the AO index has declined and the anthropogenic in- 
fluence on the AO trend appears now to be more un- 
concludes that the observed NAO trend in recent de- 
cades might very well be explained by internal variabil-
ity of the climate system.

The present paper includes a study of the relation 
between the AO index and the SAT trend based on the 
same linear regression technique as applied by Thomp-
son et al. (2000), Moritz et al. (2002), and Wu and 
Straus (2004). Our investigations differ in two major 
aspects by focusing on the trend of the mean Arctic 
SAT and by including years up to 2001. The results 
show no significant relation between the trends of the 
mean Arctic SAT and the AO index.

The paper has the following structure. Section 2 gives 
a brief presentation of the data, and section 3 describes 
the numerical procedures. Aspects of the ANET are 
found in section 4, and in section 5 regression analyses 
linking the Arctic SAT and the ANET are presented. 
Section 6 deals with the linkage between the Arctic 
SAT trend and the trends in both the ANET and the 
AO. Concluding remarks are found in section 7. Ap- 
pendix A describes how the ANET has been corrected; 
a procedure that was necessary owing to a mass incon-
stistency encountered in the ERA-40 dataset. A defini-
tion of the symbols, used in the present paper, is found 
in appendix B.

2. Data

The 45-yr global reanalysis, ERA-40 (Uppala et al. 
2005), from ECMWF has been used in this study. A 
spectral T159 model with hybrid coordinates and 60 
vertical layers extending from 10 m to 0.1 hPa, was used 
within the ERA-40 project. We use vertical integrals of 
the quantities needed for the ANET calculations. 
These quantities are all extracted directly as products 
from the reanalysis and are calculated in model-space 
hybrid coordinates and extrapolated to a 0.5° latitude 
and longitude grid. We use the SAT and SLP fields on 
a 2.5° × 2.5° grid. The 44-yr period from 1958 to 2001 
is used. The dataset is provided by the ECMWF data 
server.

The only other global reanalysis encompassing more 
than 40 years is the earlier reanalysis (Kalnay et al. 
1996) provided by the National Centers for Environ-
mental Prediction–National Center for Atmospheric 
Research (NCEP–NCAR). The reliability of the SAT 
field from this reanalysis has, however, been ques-
tioned. In the NCEP reanalysis project, SAT observa-
ations were not used in deriving the analyzed SAT field. 
The analyzed 2-m temperature was instead obtained 
from the analyzed temperatures at the model levels. In 
the ERA-40 reanalysis project, on the other hand, the 
2-m temperature observations as well as the back-
ground temperatures at the lowest model level and the 
surface were used in a separate analysis to derive the 
analyzed 2-m temperature field. Simmons et al. (2004) 
compared the SAT field from the two reanalyses with 
an observational dataset and conclude that ERA-40 is 
the most accurate of the two in all but the earliest years. 
They note, in addition, that the ERA-40 relative to the 
NCEP reanalysis benefits from improvements that have 
taken place in the period between the execution of the 
two projects, for example, improvements in data assimil-
ation technique, increased realism of the models, and 
the incorporation of new observing systems.

The SAT trends from 1979 to 2001 are shown in Fig. 
1. The trends reach 0.5°C decade⁻¹ in large localized 
parts of the American and Eurasian continents and the 
Arctic Ocean. In limited parts of the Arctic area they 
even reach 1°C decade⁻¹; for example, in northern 
Canada and in the vicinity of Svalbard.

The polar amplification of the SAT trend is evident 
from the solid curve in Fig. 2. The curves in Fig. 2 give 
the means of the SAT trends north of a given latitude. 
At 60°N, for instance, the curves give the zonal and 
meridional mean of the SAT trends from 90° to 60°N. 
The decline of the solid curve with decreasing latitude 
indicates that the mean trend for the polar area is larger 
than that for the NH as a whole. The local maximum 
around 68°N reflects the large SAT trends at the north- 
ern rims of the continents (Fig. 1).

Rigor et al. (2000) have estimated the SAT trends in 
the Arctic region for each season separately for the 
period 1979–97 (their Fig. 9). Their results from the 
Arctic sea area are to some extent based on tempera-
ture records from buoys deployed within the Interna-
tional Arctic Buoy Program (IABP) and from Russian 
North Pole drift stations. In the spring season, they find 
SAT trends exceeding 2.5°C decade⁻¹ in certain parts 
of the Arctic area. We have calculated the SAT trends
for 1979–97 separately for the individual seasons (not shown) in order to compare the results. On the continents, ERA-40 and the results presented by Rigor et al. (2000) agree well, in magnitude as well as regards the spatial distribution. Over the Arctic Ocean discrepancies between the two datasets are encountered, where ERA-40 shows smaller trends in some areas. However, the present intent is not to provide an exact estimate of the trends but rather to judge whether the trends are associated with midlatitude circulation indicators, such as ANET or the AO. Thus, although biases may be found over the Arctic Ocean in the ERA-40 reanalysis, the use of reanalysis data, rather than observations, provides an internally consistent dataset.

3. Methods

a. Energy budget

The atmospheric potential, internal, kinetic, and latent energy per unit mass of air are given by

\[ \Phi = g \zeta, \]
\[ I = c_i T, \]
\[ k = \frac{1}{2} \mathbf{u} \cdot \mathbf{u}, \]
\[ H = Lq. \] (3.1)

The sum of these four quantities yields the total energy per unit mass of air. (Symbols are defined in appendix B.) In pressure coordinates, following Kasahara (1974), the total energy budget of the atmosphere in the polar region north of a given latitude \( \phi_0 \) is given by
\[
\frac{\partial}{\partial t} \int_{M_A} (k + I + \Phi + H) \, dm = \int_{M_A} \left( Q_i + u \cdot F + Q_i \right) \, dm + \int_{\phi=\phi_0}^{\phi=\phi_t} \left( k + c_p T + gz + Lq \right) \frac{dp}{g} \, d\eta \, dx,
\]  
\tag{3.2}
\]

where the domain \(M_A\) represents the entire atmosphere north of \(\phi_0\) and \(dm = g^{-1} dx dy dp\), and \(u\) is the meridional wind component. Equation (3.2) states that the rate of change of the total energy content of the atmosphere north of latitude \(\phi_0\) is equal to advection of energy northward across \(\phi_0\) plus terms comprising sources, sinks, and transformations. The main source and sink in \(Q_i\) is absorption and emission of shortwave and longwave radiation, respectively, but \(Q_i\) also includes changes of energy due to heat conduction (especially at the lower boundary). The term \(Q_i\) includes energy change due to fluxes of \(\text{H}_2\text{O}\) gas molecules across the boundaries. In addition, \(Q_i\) and \(Q_i\) both comprise transformations of energy associated with evaporation and precipitation, and \(Q_i\) and \(u \cdot F\) both include transformations due to frictional dissipation. The sum of these terms adds up to large energy fluxes across the top and bottom boundaries, whereas the corresponding horizontal fluxes are very small. Therefore, to a good approximation, the last term on the rhs of Eq. (3.2) determines the total energy flux across \(\phi_0\). In model hybrid coordinates this term can be written as

\[
\int_{\phi=\phi_0}^{\phi=\phi_t} \frac{1}{g} \int_0^1 (k + c_p T + gz + Lq) u \frac{\partial p}{\partial \eta} \, d\eta \, dx,
\]  
\tag{3.3}
\]

where the integral, denoting the ANET, is calculated directly in model space. We focus on \(\phi_0\) equal to 60°N since at this latitude, the energy transport is a result of the midlatitude circulation patterns. Furthermore, 60°N is often assumed to constitute the Arctic boundary (e.g., ACIA 2004).

b. Mass inconsistency

It has previously been noted that the two earlier reanalyses (NCEP from the NCEP–NCAR and ERA-15 from ECMWF) are associated with large mass budget inconsistencies (Trenberth 1997). ERA-40 is no exception. Figure 3b shows the mass transport across 60°N when this mass correction has been applied. The low frequency variability is no longer present and the long-term mean is slightly positive, consistent with an overall flux of water vapor into the Arctic where, as a mean, precipitation is larger than evaporation.

The mass continuity for a unit column of air is given by

\[
\frac{\partial p_s}{\partial t} + \nabla \cdot \int_0^{\rho_s} \left( 1 - q \right) dp = g(E - P).
\]  
\tag{3.4}
\]

This constraint includes the continuity of dry air and water vapor but neglects the sources and sinks associated with other species, such as \(\text{CO}_2\) and \(\text{CH}_4\), which are several orders of magnitude smaller than those of water vapor. The basic idea of the mass correction suggested by Trenberth (1991) is that any imbalance in Eq. (3.4) can be assigned to the divergent wind field. However, the \(g(E - P)\) term is also highly uncertain. The evaporation is poorly known and the ERA-40 has also shown problems with reproducing the precipitation, especially in the Tropics (Uppala et al. 2005). By subtracting the water budget from Eq. (3.4), the mass balance of dry air is obtained. The mass balance is now dependent on the specific humidity, \(q\), instead of on \(g(E - P)\):

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \int_0^{\rho} \left( 1 - q \right) dp + \nabla \cdot \int_0^{\rho} \left( 1 - q \right) u dp = 0.
\]  
\tag{3.5}
\]

The mass budget inconsistency in ERA-40 yields that the lhs is typically not equal to zero. Let \(u^2\) represents

![Figure 3](https://example.com/fig3.png)

**FIG. 3.** The total mass flux across 60°N: (a) the uncorrected mass flux as it appears in the ERA-40 reanalysis and (b) the mass flux after a barotropic wind correction has been applied.
the horizontal wind field in ERA-40. A residual wind field \( \mathbf{u}' \) can then be found such that the difference \( \mathbf{u} = \mathbf{u}^b - \mathbf{u}' \) satisfies Eq. (3.5). Subsequently, the transport of energy can be corrected by subtraction of the unrealistic part associated with \( \mathbf{u}' \). Here, a barotropic (height independent) \( \mathbf{u}' \) field has been used. This correction does not take into account the vertical correlation of the energy and the residual wind fields. However, the major part of the mass inconsistency is removed by this first-order correction (Trenberth 1997). When estimating \( \mathbf{u}' \) by Eq. (3.5), an inverse divergence operation is needed. For that purpose, we used the SPHERPACK software provided by NCAR (Adams and Swarztrauber 1997). Appendix A provides a further description of how the ANET was corrected using vertical integrals from ERA-40.

c. Regression analysis

A linear regression technique, as proposed, for example, by Wu and Straus (2004), has been applied in order to study the linkage between the variability of the Arctic SAT field and the midlatitude circulation. Using daily data, the SAT field north of 20\(^\circ\)N has been regressed on the ANET across 60\(^\circ\)N. Regressions have been computed for different time lags of the ANET relative to the SAT field. The climatology of the SAT field and the ANET has been removed prior to performing the regressions.

When studying the linkage between trends, monthly means of the SAT field, the AO index, and the ANET are used. The monthly means reduce the effects of a time lag on time scales of days between the time series. The AO is obtained from monthly means of the SLP field. The AO index is here defined as the principal component (PC) associated with the leading empirical orthogonal function (EOF) of the monthly mean SLP field north of 20\(^\circ\)N.

The statistical significance of the regressions is estimated by applying a Monte Carlo approach. The SAT field is regressed on artificial time series with the same power spectrum as, for example, the ANET, but with arbitrary phases of the modes. These regressions with the artificial time series are compared to the original regression for each spatial grid point. At a given grid point, the SAT trend associated with the ANET is significantly different from zero at, say, a 99% confidence level if less than 1% of the artificial regressions show trends that are numerically larger than the one from the original regression. For example, if the ANET is associated with a SAT trend of 1\(^\circ\)C decade\(^{-1}\), which is significantly different from zero at a 99% level, it means that less than 1% of the arbitrary time series are associated with a SAT trend above 1\(^\circ\)C or below \(-1\(^\circ\)C.

Henceforth the specification “different from zero” is omitted, and in the above example, it is simply stated that the trend is significant at a 99% level. All Monte Carlo simulations are based on at least 5000 arbitrary time series.

4. Atmospheric northward energy transport at 60\(^\circ\)N

The monthly means of the ANET across 60\(^\circ\)N for the period 1958 to 2001 are shown in Fig. 4a. The 44-yr mean of the transport is 3.0 PW. This is consistent with the estimate given by Trenberth and Stepaniak (2003) who calculated the transport from the NCEP reanalysis, but larger than the value of 2.3 PW found by Oort and Peixóto (1983) using rawinsonde measurements from the period 1963–73. The ANET shows distinct variability over the year with maxima and minima in the winter and summer season, respectively. Variability is also found on interannual time scales (>1 yr) as evident from Fig. 4b showing the ANET when the annual cycle has been subtracted. The variability includes a positive trend from the mid-1980s to the mid-1990s.

The variability of ANET at 60\(^\circ\)N as a function of longitude is represented by the standard deviations in Fig. 5. Figures 5a–d show the standard deviation on all, interannual, intra-annual, and annual time scales, respectively. Since variances, but not standard deviations, for a given longitude, are additive for a decomposition of a time series into different time scales, the square of the value for all time scales (Fig. 5a) equals the sums of the squared values for the specific time scales (Figs. 5b–d).

Most of the variability is captured by processes on intra-annual time scales (<1 yr). On these time scales, the maximum variability is found in the regions from the Atlantic Ocean and well into Russia and in the vicinity of the Pacific Ocean. This is consistent with the findings of Overland and Turet (1994), who estimated the flux across 70\(^\circ\)N. The maxima close to the oceanic sectors reflect that the ANET across 60\(^\circ\)N is an integrated property of the midlatitude circulation: On these time scales, these regions are characterized by an eastward flow of baroclinic weather systems, which are known to play a key role for the ANET in the midlatitudes (Oort and Peixóto 1983).

Also the interannual time scales, including the trend, show the largest variability in the Atlantic and Pacific sectors adjacent to the Icelandic and Aleutian lows, respectively, and hence close to the major centers of origin of baroclinic weather systems at the NH midlatitudes. These maxima are presumably associated with changes in the properties of these weather systems.
This idea is supported by studies indicating that the strength and frequency of cyclone systems entering the Arctic region have increased in recent decades (McCabe et al. 2001; Zhang et al. 2004). Additionally, cyclone activity has intensified in the Pacific and in the Atlantic during 1958 to 1998 as suggested by Geng and Sugi (2001) and Graham and Diaz (2001), respectively, on basis of the NCEP reanalysis. Chang and Fu (2003) note that the reanalysis data should be handled with caution as regards such trend estimates since spurious climate signals might have been introduced in the reanalysis as a result of, for example, changes in the observational network and quality of the observations. Since storm track changes in the Atlantic region are dynamically linked to changes of the mean flow, Chang and Fu focused on the mean flow (which is assumed to be better represented in the reanalysis) to show that the Atlantic storm tracks have, indeed, intensified. This in-
tensification is also found at higher tropospheric levels (Chang and Fu 2002).

5. Sensitivity of the Arctic surface air temperature to the midlatitude circulation

To explore the sensitivity of the Arctic SAT to changes in the midlatitude circulation, the Arctic SAT field has been regressed on the ANET across 60°N. The regressions have been performed with negative and positive time lags of the ANET for the period 1979 to 2001, and a 7-day running mean filter has been applied. Figure 6 shows the results for time lags ranging from −8 to 12 days with 4-day steps. For convenience, the regressions have been scaled using the standard deviation of all regressions since this procedure ensures that the regressions in this case can be directly compared.

For positive lags (i.e., when the ANET leads the SAT field), positive values of the regressions are found in the polar area north of 60°N. At lower latitudes, negative values are found on the continents. These patterns are in agreement with a general hypothesis that transport of energy across 60°N subsequently warms the areas north of and cools the those south of 60°N. The 4- and 8-day lag results show maxima close to the Pacific and Atlantic sectors, that is, close to the longitudes where the largest variability of the ANET at 60°N is present (Fig. 5a). In addition, these longitudes are close to the areas that are heavily exposed to baroclinic weather systems. These circumstances suggest that the Arctic temperature field is sensitive to variability of the midlatitude circulation.

For negative time lags, the regressions show almost reversed patterns compared to those from positive time lags. Hence large (small) energy transport is preceded by a larger (smaller) than usual meridional temperature
Fig. 6. Regression modes of the SAT field on the ANET across 60°N with different time lags. The regressions have been scaled by the standard deviation of all regressions. Solid and dotted lines represent positive and negative contours, respectively. The contour interval is 1 and the zero line is omitted; light and dark shading indicates significance at a 99% and 99.9% level, respectively.
The zonal structure of the evolution is more easily seen from Fig. 7, which shows zonal means of the scaled regressions. Large (small) ANET across 60°N preceded by warmer (colder) than usual conditions in the midlatitudes and followed by warmer (colder) conditions in the Arctic area and colder (warmer) conditions in the midlatitudes. These results are significant at the 99.9% level.

To determine the quantitative influence on the SAT field, which the variability of the ANET across 60°N gives rise to, a difference between composite of positive and negative episodes exceeding one standard deviation has been estimated and is shown in Fig. 8. It is evaluated for the 5-day lag since this regression shows the largest ANET variability influence on the temperature field (Fig. 7). It is found that the variability of the ANET causes the Arctic SAT variability to exceed 1°C in a major part of the area north of 60°N and 3°C in the areas adjacent to the Atlantic and Pacific sectors. Figure 9 shows the zonal means of the standard deviations of the total SAT field and the part of the SAT field associated with the ANET across 60°N. In terms of standard deviation the ANET describes around 10% of the total SAT variability at most latitudes in the Arctic.

We also studied the importance of the synoptic time scales in the above regressions by recalculating the regressions from filtered data where variability on time scales exceeding one month has been removed (not shown). Similar patterns were obtained for the synoptic time scales compared to those for the unfiltered data. Again this emphasizes the importance of the baroclinic systems for the linkage between the variability of the ANET and the Arctic SAT. In all of these studies, the period 1979 to 2001 has been used. We have verified, in addition, that the conclusions above also hold for the entire period 1958–2001.

### 6. Arctic surface air temperature trend and midlatitude circulation

#### a. Atmospheric northward energy transport

The part of the SAT trends associated with ANET across 60°N is shown in Fig. 10. The field shows the linear trend of the regression based on monthly mean data using the method described by Wu and Straus (2004). The trends reach 0.05°C decade⁻¹ at locations in the northwestern part of the North American continent. They reach 0.1°C decade⁻¹ in Greenland and over the Greenland and Barents Seas, and show values below −0.05°C in northeastern Siberia, Baffin Island, and over the Labrador Sea. Even though some of these trends are significant at the 99% level (suggesting that the result is robust), they constitute only a minor part of the total SAT trend (Fig. 1).

The polar means of the SAT trends associated with ANET across 60°N are given by the dotted curve in Fig. 2. The polar mean of the SAT trend north of 60°N reaches 0.4°C decade⁻¹ of which about 0.03°C or 7% is associated with the ANET. This result is significant at a 98% level. To test whether this significance level is reached as a result of the trend in the ANET, an alternative significance test has been performed with an additional constraint: All the artificial time series in the Monte Carlo test have the same interannual variability (including the trend) as the ANET. The result showed that the polar mean down to 60°N of the SAT trend associated with the ANET was significant at the 95% level.

Alexeev (2003) studied the response to a doubling of CO₂ for an aquaplanet (lacking continents) climate model with a globally constant albedo and hence no ice–albedo feedback. In spite of this restriction, the results showed a warming response that included a polar amplification. This was studied further by Alexeev et al. (2005), who added a uniform forcing to GCMs also lacking the ice–albedo feedback. The initial response was a uniform surface warming, but the warming leads to an increase of the meridional heat transport that, in turn, implied a polar amplification. Figure 2 indicates...
the magnitude of this effect estimated in the real world using data from a period where a global surface warming has been encountered. It is found here that only a small part of the Arctic SAT trend can be linearly attributed to the ANET, suggesting that the meridional heat transport during the 1980s and 1990s was only a minor cause of the polar SAT amplification. However, the high significance level reached by the results in Fig. 2 leads to the conclusion that even though the impact is small, the trend of the mean Arctic SAT is associated with changes of the ANET across 60°N and, accordingly, with the midlatitude circulation.

It has been verified that the conclusion stated above holds even if important settings are varied. The trend of the polar mean SAT north of 60°N is associated with the ANET at a 97% significance level even if the trends are calculated from 1970 or 1985 to 2001 or if the ANET is calculated at 55° or 65°N instead of at 60°N.

Figure 11 shows a seasonal separation of the results in Fig. 2. It is found that a considerable part of the mean Arctic SAT trend down to 60°N can be linked to the ANET during the spring and autumn season. In winter, the impact is negligible and even reversed if averages down to more northern latitudes are considered. This negative impact is coupled to an overall small declining tendency of the ANET in the winter season. The linkages found during spring and autumn for SAT trend averages down to 60°N reach a 94% and 99% significance level, respectively, whereas the corresponding results for the winter and summer season are not statistically significant.
b. The Arctic Oscillation

The relation between the AO and the SAT trend has been studied earlier by, for example, Thompson et al. (2000), Moritz et al. (2002), and Wu and Straus (2004). The AO has attracted much interest and, since it and the ANET across 60°N are both indicators of the mid-latitude circulation, the relation between the AO and the Arctic SAT trend is also investigated here in order to compare with the results based on the ANET.

Figure 4c shows the AO index, scaled by its standard deviation. It has an overall positive trend from the late 1970s to the early 1990s and thereafter a negative tendency. A positive trend is found in the ANET from the mid 1980s but, in contrast to the AO index, the ANET maintained a high level throughout the 1990s (Fig. 4b). Consequently, the two time series manifest uncorrelated interannual development in the 1990s.

The part of the SAT trends that is associated with the AO index is shown in Fig. 12. Positive trends reaching 0.05°C decade⁻¹ are primarily present on the continents and are only found over the nearshore regions of the Arctic Ocean. The dashed line in Fig. 2 shows the polar means of the SAT trends that are associated with the AO index. The mean of the trends north of 60°N appears to be slightly positive, but this result is not significant. Weak and statistically insignificant linkages are also found for the individual seasons (Fig. 11). We have recalculated these regressions using the PC associated with the leading EOF of the 500-hPa geopotential height field instead of the AO index based on the SLP (not shown). These results did not either reveal any significant trends.

The impact of the AO on the SAT trends is limited to the boundary regions of the Arctic whereas the part of the SAT trends explained by the ANET is located in large Arctic areas. A strong AO is related to stronger-than-usual zonal winds in the midlatitudes and, presumably, to eastward advection of heat from the Atlantic Ocean into Eurasia, implying warmer-than-usual winter conditions there (Thompson et al. 2000). Strong ANET, on the other hand, appears to be not only as-
associated with the strength of the zonal flow, but is also determined by other processes than those associated with a strong AO.

The fact that the ANET and the AO show opposite trends in the 1990s (Figs. 4b and 4c) could be a consequence of changes in the baroclinic structure of the synoptic-scale waves in the Pacific and Atlantic sectors; changes that are not primarily associated with the strength of the zonal flow. Reinhold (1986) showed that the amplification and vertical structure of the synoptic-scale waves also depend on the static stability of the atmosphere and the surface friction. It follows that, even though the zonal flow and hence the AO index are unchanged, the baroclinic structure of the waves might change in such a way that the northward heat transport increases. Chang and Fu (2003) found that, even though part of the storm track intensification in the Atlantic sector might be associated with the AO, a significant part of the intensification cannot be linearly attributed to this mode.

The period January through March is the active season of the AO (Thompson and Wallace 2000) when the mode shows its highest vertical extent reaching into the lower stratosphere (Baldwin and Dunkerton 1999). The SAT trends related to the AO index during this season are similar to those for the entire year (Fig. 12) except that the amplitudes are much larger. Maps showing the trends from January through March have been presented by, for example, Thompson et al. (2000), Moritz et al. (2002), and Wu and Straus (2004). In certain areas

Fig. 11. As in Fig. 2, but for the individual seasons: (a) December–February (DJF), (b) March–May (MAM), (c) June–August (JJA), and (d) September–November (SON).
in northern Eurasia the trends reach 0.5°C decade⁻¹; results significant at the 95% level. However, the polar mean of the SAT trends shows no significant linkage to the AO, even in the period January through March.

7. Concluding remarks

The SAT in the Arctic region is sensitive to variability of the midlatitude circulation. This conclusion has been drawn since large (small) ANET across 60°N is succeeded by warming (cooling) of the Arctic region with a maximum (minimum) about 5 days later (Fig. 7). A large energy transport is followed by warming, especially north of the Atlantic and the Pacific sectors. This suggests that the baroclinic weather systems developing around the Icelandic and Aleutian lows are important for the energy transport.

In addition, the ANET across 60°N has an overall increase during 1979–2001 (Fig. 4b). This trend coincides with an increase in the strength and frequency of cyclones entering the Arctic area (McCabe et al. 2001; Zhang et al. 2004) and with an intensification of storm tracks in the Atlantic sector (Chang and Fu 2003). The increase has continued through the major part of the 1990s; this is in contrast to the development of the AO index, which during that period has shown negative tendencies (Fig. 4c).

A small, but statistically significant, part of the SAT trend in the Arctic region can be linked to the ANET across 60°N (Figs. 2 and 10). In some areas, these trends differ significantly from zero at a 99% level. Hence, it is concluded that, according to the ERA-40 reanalysis, changes in the midlatitude circulation have had an effect on the Arctic SAT trend. However, the linkage is weak and presumably of much less importance than local processes such as those related to the snow and ice feedbacks. A stronger linkage between the Arctic SAT trend and the ANET is found for the spring and autumn season.

Although these results suggest that through the 1980s and 1990s the midlatitude circulation has affected the Arctic SAT trend, the mechanisms involved need to be further established. In particular, it would be of interest to explore whether the baroclinic structures of the synoptic-scale waves during recent years have changed in such a way that the heat transport has increased but the zonal flow remains more or less unchanged or, perhaps, even weakened. Furthermore, it is not clear why the

Fig. 12. As in Fig. 10, but for the SAT trends associated with the AO index.
Arctic SAT trend shows a considerably stronger linkage to the ANET in the spring and autumn season than during the winter months. It may be speculated that the north–south position of the polar front during spring and autumn is shifted northward in accordance with the shortening of the Arctic winter season (ACIA 2004). This shift may alter the conditions under which the mid-latitude baroclinic disturbances develop and thus affect the energy transport efficiency of the baroclinic waves (Reinhold 1986).

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APPENDIX A

Energy Transport Correction

According to (3.3), the energy transport across $\phi_0$ by the residual wind, $u'$, can be formulated as

$$I_1 = \frac{1}{g} \int_{\phi=\phi_0}^{1} \int_{0}^{1} (k + c_pT + gz + Lq) \frac{\partial p}{\partial \eta} \, d\eta \, dx,$$  

(A.1)

provided that barotropic wind residuals have been assumed. This integral comprises part of the energy transport which can be assigned to the mass inconsistency in ERA-40 dataset. To obtain the corrected energy transport, (A.1) is subtracted from (3.3).

The vertical integral in (A.1) is not obtained directly within the ERA-40 frame work. However, the following two are available:

$$I_1 = \frac{1}{g} \int_{0}^{1} (k + c_pT + gz + Lq) \frac{\partial p}{\partial \eta} \, d\eta,$$  

(A.2)

$$I_2 = \frac{1}{g} \int_{0}^{1} c_p T \frac{\partial p}{\partial \eta} \, d\eta,$$

which can be combined as

$$I_1 + \frac{R}{c_p} I_2$$  

(A.3)

to yield the vertical integral in (A.1). In (A.3) the dependency of $R$ and $c_p$ on the humidity has been neglected, which is not the case for the two integrals in (A.2). At 60°N the difference between the wet and dry values of these two parameters is on the order of $10^{-2}$ and the fraction in (A.3) on the order of $10^{-3}$. Hence, the effect of humidity variations in (A.3) can be neglected.

A comparison between the uncorrected and corrected mass transports across 60°N provides an idea of the development of the spurious mass fluxes (Fig. 3). The annual cycle, the interannual variability, as well as much of the faster variability are removed from the mass transport by the correction. The ANET, as it appears in the ERA-40 data, shows the same overall interannual structure as that found in the uncorrected mass transport (not shown). Like the correction of the mass flux, the correction of the energy transport affects the variability at all time scales. The correction implies, for instance, that the ANET does not show the same interannual development as the uncorrected mass flux does, and the annual cycle of the ANET is diminished.

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