INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **23**: 399–404 (2003)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/joc.885

IMPACT OF THE EXTRATROPICAL DYNAMICAL MODES UPON TROPOSPHERE TEMPERATURE USING AN APPROACH BASED ON ADVECTION OF TEMPERATURE

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Received 12 October 2001
Revised 26 November 2002
Accepted 26 November 2002

ABSTRACT

Advection of temperature (AT) is used to diagnose the influence of changes in extratropical atmospheric circulation on air temperature. AT is calculated at three different pressure levels (850, 500 and 200 hPa) for the period 1958–98 using NCEP–NCAR reanalysis data. Global and hemispheric annual series of AT have a common feature consisting of positive values and trends at 850 and 500 hPa and negative values and trends at 200 hPa, together with quasi-biennial and quasi-quadrennial oscillations for most of the series. Significant correlations were found between most of the Northern Hemisphere and global AT series with the Arctic oscillation and between most of the Southern Hemisphere and global AT series with the Antarctic oscillation. Copyright © 2003 Royal Meteorological Society.

KEY WORDS: advection of temperature; Arctic oscillation; Antarctic oscillation

1. INTRODUCTION

A number of observational studies have identified decadal trends in both Northern Hemisphere (NH) temperature and frequency occurrence of dominant atmospheric modes of variability. For instance, Hurrell (1996) estimated that almost half of the interannual variance of NH air surface temperature in the extratropics, in recent decades, is explained by large-scale circulation patterns. The increase in global temperature is associated with changes in atmospheric circulation producing negative temperature anomalies over the oceans and positive temperature anomalies over the continents (Wallace, 1996). Considering the larger heat capacity of the oceans, the result is that the hemispheric mean surface air temperature is largely determined by the temperature of the continents. The region of strongest variability is located in the extratropics, where the dominant modes of atmospheric variability are the annular ones: the Arctic oscillation (AO) in the NH and the Antarctic oscillation (AAO) in the Southern Hemisphere. There is an exciting debate about the best paradigm to define the northern mode: a hemispheric paradigm (AO) or a regional one centred on the Atlantic area, the North Atlantic oscillation (NAO). Many scientists agree with Wallace (2000), who considers both as the same phenomenon. If we consider the northern mode as being represented by a regional paradigm (NAO), the influence on NH surface temperature is estimated to be about one-third of its total variance. Hurrell (1995, 1996) showed that the positive trend of the NAO in recent decades accounts for considerable regional surface

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warming over Europe and Asia and for regional cooling over the northwestern Atlantic. If we consider the northern mode as an annular hemispheric mode (AO) (Thompson and Wallace, 1998, 2000), then the influence on hemispheric temperature is also present (Thompson *et al*., 2000). In the Southern Hemisphere the AAO can be considered as a dynamical twin of the AO. The positive polarity of the AAO is associated with cold anomalies over most of Antarctica, warm anomalies over the extratropics and cold anomalies again over the tropics (Thompson *et al*., 2000).

Our hypothesis is that, on an interannual time scale, the fluctuations in the hemispheric circulation pattern represented by the dominant internal dynamical modes of extratropical atmosphere (AO and AAO) explain an important part of the tropospheric temperature variability. Our approach is to analyse the advection of temperature, a variable that links circulation with temperature, and whose value is in itself representative for changes in tropospheric temperatures due to changes in tropospheric circulation patterns.

2. DATA

The data set used consist of 41 years (1958–98) extracted from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis project. The NCEP–NCAR reanalysis project (Kalnay *et al*., 1996) is based on a data assimilation scheme performed with a T62 model with 28 vertical sigma levels and the operational statistical interpolation (SSI) procedure for assimilation. The data sources include rawinsonde profiles, surface marine reports from the comprehensive ocean–atmosphere data set (COADS), aircraft observations, surface land synoptic reports, satellite soundings from the Tiros operational vertical sounder (TOVS) and other platforms, surface wind speeds from the Special Sensor Microwave Imager, and satellite cloud drift winds. The reanalysis fields of atmospheric data provide daily mean atmospheric data with global coverage. The horizontal resolution in our study is $2.5^{\circ} \times 2.5^{\circ}$.

3. METHOD

Using temperature and wind (zonal u and meridional v components) data at three different levels (850, 500 and 200 hPa) for the period 1958 to 1998, daily values of advection of temperature (AT) for every grid point were calculated. At a gridpoint (λ, φ), AT was calculated according to the following expression:

$$\mathrm{AT} = -\frac{u_{\lambda,\varphi}(T_{\lambda+2.5^{\circ},\varphi} - T_{\lambda-2.5^{\circ},\varphi})}{2\Delta x} - \frac{v_{\lambda,\varphi}(T_{\lambda,\varphi+2.5^{\circ}} - T_{\lambda,\varphi-2.5^{\circ}})}{2\Delta y}$$

where φ is latitude, λ is longitude, $\Delta x = R_{\mathrm{T}}2.5\cos$, $\Delta y = R_{\mathrm{T}}2.5$, and $R_{\mathrm{T}} = 6350$ km (mean Earth radius).

Then, global and hemispheric annual mean values of AT were estimated from daily means for every grid point, as well as mean values for latitude belts (0–30°, 30–60°, 60–90°), using an areal correction factor.

To study the time behaviour of AT, singular-spectrum Analysis (SSA) (Broomhead and King, 1986; Vautard and Ghil, 1989) was applied to decompose annual series of AT into trends, oscillations and noise. SSA is designed to reconstruct parts of the underlying dynamics of a time series, without prior knowledge of the equations that generated it, by using embedding techniques (Vautard *et al*., 1992). The statistical significance of the principal components (PCs) obtained using SSA was determined by a Monte Carlo test. Then, three spectral-analysis techniques were used to reduce the risks of spurious results and enhance their reliability. The first is the multi-taper method (MTM; Thomson, 1982) which estimates the total power spectrum of a time series, and determines its line frequencies by harmonic analysis. It is designed to reduce the variance or spectral estimates and is particularly well adapted to analyse short time series. The second is the Blackman–Tukey (BT) method, which begins with the calculation of the autocorrelation function (ACF) of the time series. The spectrum is then calculated from the Fourier transform of the ACF. The third method is the maximum entropy method (MEM) is a powerful method for estimating line frequencies in an autoregressive time series (Childers 1978). The MEM is very efficient for detecting frequency lines for stationary time series. An oscillation was considered significant only when it was significant after applying the three spectral methods.

Afterwards, the time series of AT were correlated with instrumental indices of the AO and the AAO. The AO index was calculated as the first PC (PC1) of the sea-level pressure field from the NCEP–NCAR reanalysis, in the NH. The AAO index is based on the PC1 of the 850 hPa height field from the NCEP–NCAR reanalysis, poleward of 20°. We use the AO index instead of the NAO index because we are interested in the hemispheric modes rather than the rationalized ones.

4. RESULTS

Figure 1 shows the temporal series of the mean AT for the whole globe, Northern and Southern Hemispheres and 30–60° and 60–90° latitude belts. Significant trends at the 95% confidence level are also displayed by means of the regression line. From a visual inspection of Figure 1, a common feature consisting of positive values of AT at 850 and 500 hPa and negative values at 200 hPa, for the global and hemispheric AT and for both hemispheres is identified. The pattern is opposite for the 60–90° latitude belt AT averages. Significant upward trends are found in Southern Hemisphere middle latitudes (30–60°) for both 850 and 500 hPa. These trends are strong enough to be seen in the Southern Hemisphere and even in the global averages. On the other hand, in the upper troposphere (200 hPa) significant downward trends are found for middle and upper latitudes in the NH, which is also seen in the NH averages but not in the global ones.

The features described above are consistent with the greenhouse warming fingerprint revealed by numerical experiments with general circulation models (Bengtsson, 1999). The spectral characteristics of the AT time series have been investigated and the results are displayed at the bottom of each series in Figure 1. The first box indicates the PCs in the SSA that are significant after a Monte Carlo test, the temporal domain of the oscillation is shown in the second box and the percentage of the total variance of the series accounted for by each significant PC is displayed in the third box. At 850 hPa all the series have a significant oscillation band centred at 4 years (quasi-quadrennial — QQ), and most of them also have a second oscillation band centred at 2 years (quasi-biennial — QB). Significant oscillations are found at 500 hPa only in the higher latitude belts, being QB for the NH and QQ for the Southern Hemisphere. At 200 hPa the QQ oscillation found in the three series corresponding to the Southern Hemisphere dominates in the temporal behaviour of the whole globe series, which also shows this QQ oscillation. QB and QQ oscillations have also been found in the global surface temperature (Ghil and Vautard, 1991), in El Niño–Southern Oscillation phenomenon (Jiang *et al*., 1995) and in the NAO (Pozo-Vazquez *et al*., 2001). It is worth remarking that the QB and QQ oscillations reproduced almost 60% of the total interannual variance of the global average of the AT.

To find whether the interannual variability of the AT is dominated by variability in the atmospheric circulation, the AT series were correlated with temporal series of the AO and AAO indices (Table I), which represent the two main modes of extratropical climate variability. AO and AAO indices were correlated with global AT series and with the three series of the corresponding hemisphere. AO and AAO clearly dominate the interannual variability of AT series at 200 and 500 hPa. All AT series were significantly correlated with AO and AAO, reaching correlation coefficients higher than 0.8 for AO with global 500 hPa AT, AO and AAO with hemispheric 500 hPa AT and AO with NH 200 hPa AT.

There were positive correlations at 500 hPa and negative ones at 200 hPa, which suggests that AT at 500 hPa is more sensitive to changes in zonal advection and AT at 200 hPa more sensitive to changes in meridional advection. The meridional component of AT at 200 hPa over the Atlantic region is dynamically related to the jet stream. Furthermore, the intensity and position of the jet stream are linked with the intensity and position of storm tracks over the North Atlantic and with the NAO phases, as several studies have shown (Rogers, 1990; Hurrell and van Loon, 1997).

Large magnitudes of correlation coefficients are found for both hemispheres at the 500 hPa level due to the fact that the influence of continents and oceans as heat sources and sinks diminishes with height. In this case, atmospheric circulation become the main factor in controlling the temperature field, and AT indices are highly correlated with circulation-type indices (AO and AAO indices). The correlation coefficients between AT and circulation indices are not statistically significant at lower levels in the troposphere. The only case in which a clear relation is found between AT and AO/AAO indices at 850 hPa level is for the latitudinal

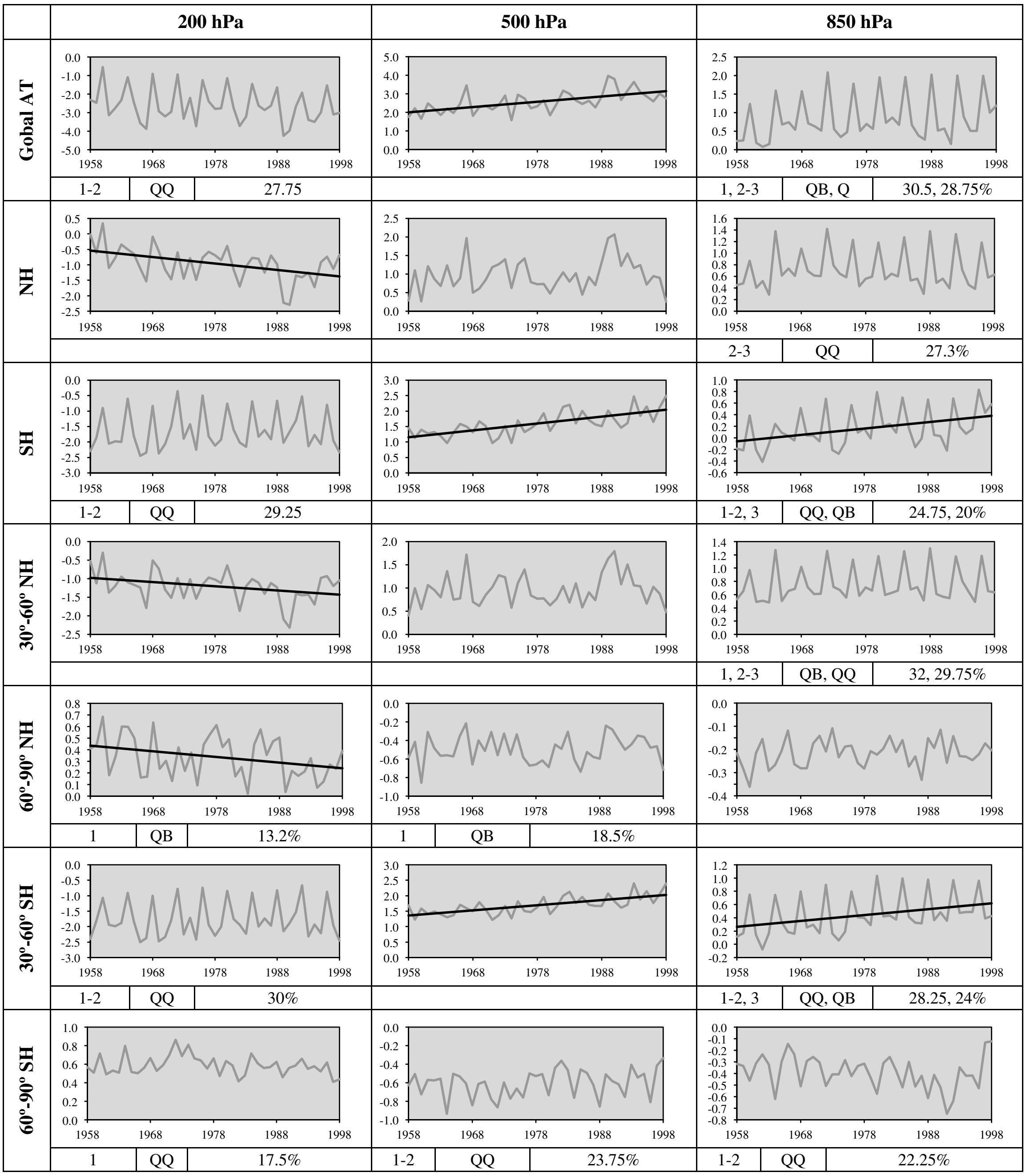

Figure 1. Global, hemispheric and latitude belt AT series ($\times 10^{-5}$ ks^{-1}) at 200, 500 and 850 hPa. Only significant trends are displayed on the series. At the bottom of each series the first box indicates the PCs in the SSA that are significant after a Monte Carlo test, the second box indicates the temporal domain of the oscillation and the third box indicates the percentage of the total variance of the series accounted for by each significant PC

belt 60–90° in the NH. The atmospheric circulation serves to transport the heat energy gained through the surface fluxes over the North Atlantic and North Pacific to the continental and ice-covered regions of the central Arctic, where the net surface flux is small. In this context, it is noteworthy that, poleward of 70°, the NH is primarily an ice-covered ocean. Therefore, the NAO/AO influence on the temperature field is enhanced

Table I. Correlations between AT series and the main mode of variability in each hemisphere: AO (NH) or AAO (Southern Hemisphere) at three different pressure levels (200, 500 and 850 hPa). The AO index was correlated with global AT and NH series and the AAO index was correlated with global AT and Southern Hemisphere AT series

	200 hPa		500 hPa		850 hPa	
	AAO	AO	AAO	AO	AAO	AO
Global AT	−0.485**	−0.480**	0.558**	0.811**	−0.170	−0.044
Hemispheric AT	−0.379*	−0.835**	0.823**	0.857**	−0.008	−0.005
30–60° AT	−0.404**	−0.855**	0.837**	0.803**	−0.110	−0.018
60–90° AT	−0.419**	−0.536**	0.542**	0.609**	0.191	0.407**

*$p < 0.05$, **$p < 0.01$.

here by its control on sea-ice extent (Bengtsson, 1999), leading to a higher correlation coefficient between atmospheric circulation and AT index than in the case of the Southern Hemisphere.

5. CONCLUSIONS

In this study, AT has been used to diagnose the influences of changes in the atmospheric circulation on the low, mid and upper troposphere with the following main conclusions.

The sign and trend of the AT suggest that changes in circulation induce a warming on the low and mid troposphere and a cooling in the upper troposphere, and this pattern has been enhanced in the last 40 years. These features are consistent with the greenhouse warming fingerprint revealed by numerical experiments with general circulation models (Bengtsson, 1999).

As for the spectral analysis, the QB and QQ oscillations account for most of the interannual variance of the global AT. The same signals have also been observed in the global temperature.

The correlations of AT with the two dominant modes of climate variability in the extratropics (AO and AAO) show that AT is clearly dominated by changes in circulation at mid and upper troposphere levels. The hemispheric differences in the land–ocean distribution modulate the relation between annular circulation and AT, with the AO index generally having a stronger correlation with the AT than the AAO.

The AO and AAO account for about 70% of the interannual variance of their respective hemispheric AT, and AO accounts for 66% of the global AT interannual variance.

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