Interpretation of Winter Warming on Northern Hemisphere Continents in 1977–94

EVTGENY M. VOLODIN AND VENER YA. GALIN
Institute of Numerical Mathematics of Russian Academy of Sciences, Moscow, Russia

(Manuscript received 16 December 1997, in final form 10 July 1998)

ABSTRACT

Northern Hemisphere December–March near-surface temperature and pressure anomalies during 1977–94 relative to those during 1946–76 are considered. To a first approximation these anomalies can be decomposed into two components. The first one reaches its maximum during 1977–88. The main features of the anomalies of 1977–88 can be obtained as the atmospheric general circulation model (AGCM) response to sea surface temperature anomalies observed during that period. The second component reaches its maximum in 1989–94. The main features of anomalies of 1989–94 relative to 1977–88 can be obtained as the AGCM response to lower-stratosphere ozone depletion observed in 1989–94.

1. Introduction

As is known from the observations, Northern Hemisphere near-surface air temperature has increased from the late 1970s up to now. The most pronounced warming occurred over the continents during the cold half of the year (Parker et al. 1994). Such a warming is associated with atmospheric circulation anomalies (Wallace et al. 1996; Zhang et al. 1997). The spatial distribution of the observed warming and the response of most of the coupled atmosphere and ocean models to the greenhouse gases increasing are quite different (Houghton et al. 1995). Including the radiation effect of anthropogenic sulfate aerosols improved the simulation of the zonal-mean annual atmospheric temperature trends (Taylor and Penner 1994; Santer et al. 1995; Mitchell et al. 1995). Nevertheless, the structure of near-surface warming and especially the pronounced warming during the cold season over the midlatitude Northern Hemisphere continents were reproduced poorly by the atmospheric general circulation models (AGCMs), even after including the sulfate aerosol forcing.

So the reasons for the observed near-surface warming are still under discussion.

The purpose of this study is to diagnose Northern Hemisphere wintertime atmospheric circulation anomalies during the period 1977–94 and to attempt to reproduce these anomalies as a response of the AGCM to external forcing.

2. Data

Monthly mean near-surface temperature for 1854–1994 (Jones et al. 1986a,b) and sea level pressure (SLP) for 1946–94, both from the National Center for Atmospheric Research Data Library, were used. Data for year $N$ denotes January, February, and March data of year $N$ and December data of year $N - 1$. Figures of the time series represent time-filtered data, where harmonics with periods shorter than 5 yr have been removed and harmonics with periods of 5–10 yr have been reduced in amplitude. For time filtering we use the method of Blackmon (1976), but the choice of method is not crucial: analogous results can be obtained using a simple 5-yr running mean. All the computations, such as the empirical orthogonal function (EOF) calculation, were carried out using unfiltered monthly mean data.

The anomaly $A$ of some value can be decomposed on the basis of the EOFs of this value $E_n$:

$$ A = \sum_{n=1}^{N} C_n E_n. $$

Here $N$ is the number of grid points in the domain, and $C_n = (E_n, A)/(E_n, E_n)^{0.5}$, where the scalar product $a$ and $b$ is defined as

$$ (a, b) = \sum_{n=1}^{N} a_n b_n \cos \varphi_n, $$

and $\varphi_n$ is the latitude of grid point $n$. Then, we can define the contribution $D_n$ of the $n$th EOF $E_n$ to the anomaly $A$ as

$$ D_n = C_n^2 (A, A). $$

This contribution is a measure of the similarity of the
anomaly pattern and the EOF pattern. The sum of the contributions of all the EOFs to the anomaly defined in this manner is equal to 1:

$$\sum_{\alpha=1}^{N} D_\alpha = 1.$$ 

### 3. Results

Figure 1a shows cold season temperature anomalies averaged over the Northern Hemisphere continents (thick line). One can see a noticeable warming during the past two decades. Taking into account this figure, let us denote the interval 1946–76 years’ data as the norm and calculate the anomalies during the interval 1977–94 with respect to this norm. Figure 2 shows the anomalies of temperature and SLP for 1977–94 with respect to the reference period 1946–76. Warming of up to 1–2 K occurred almost everywhere over the continents to the north of 45°N, and cooling of up to 0.5 K occurred over the midlatitude oceans, while the tropical oceans warmed by as much as 0.5 K (Fig. 2a). The mean temperature anomaly over the continents equals 0.50 K, while over the oceans it equals 0.11 K. These temperature changes were accompanied by SLP changes (Fig. 2b).

For further study of this problem, the EOFs of the observed monthly mean SLP field were calculated. The first and the second EOFs are presented in Figs. 3a and 3b, and their filtered expansion coefficients are shown in Fig. 1b. Now, let us note that the contributions of the first two EOFs of SLP to the SLP anomaly of 1977–94 are as large as 0.38 and 0.37, respectively, and the contribution of all the other EOFs equals 0.25. So to a first approximation, this SLP anomaly can be represented as a superposition of the first and second EOFs. It is seen that both these expansion coefficients were extremely large in 1977–94, but the maximum in the first was observed in 1989–94, while the second was large in 1977–88. Hence the SLP and temperature anomalies in these two periods must have been different. Figure 4 confirms this. Although in both periods the integral warming is almost the same (0.38 and 0.34 K over the continents and 0.08 and 0.09 K over the oceans), the spatial structure of the anomalies is quite different. In 1977–88, as compared to 1946–76, warming of up to 2–3 K occurred in Alaska and Canada and up to 1 K in western and central Siberia. In the eastern United States and in Europe cooling up to 0.5 K was observed. SLP changes of up to 6 mb were observed over the North Pacific. In 1989–94, compared to 1977–88, warming of up to 3 K was observed in Europe and central and eastern Siberia, and a cooling of up to 2.5 K was observed over eastern Canada. The SLP anomalies are negative to the north of 60°N and positive to the south of 60°N, with maxima over both oceans and Europe. The spatial correlation coefficient between the temperature anomalies during these two periods is equal to −0.02, and the corresponding correlation for SLP is equal to −0.24. Note also that the contribution of the second EOF to the SLP anomaly of 1977–88 equals 0.61, that is, larger than the contribution of all the other EOFs combined, and the contribution of the first EOF is equal to 0.00. On the contrary, the SLP anomaly of 1989–94 comes mainly from the first EOF (its contribution is equal to 0.81), and that from the second EOF is much smaller (0.12).

The projections of the SLP anomalies for each year onto the anomalies of 1977–88 and 1989–94 are shown in Fig. 1c. The projections and the expansion coefficients for two leading EOFs (Fig. 1b) look very similar. So the wintertime warming of the Northern Hemisphere observed during past two decades can be represented as a sum of two components that are almost orthogonal in space and that reached their maxima in the different periods.
Therefore one can suppose that if the observed anomalies were induced by some external forcing, then they might not be occurring in response to a single forcing but to two different forcings that were dominant during different time intervals. What kind of forcings could they be?

The temperature and SLP anomalies structure in 1977–88 look like the anomalies associated with near-equatorial warming in the Pacific (El Niño) (Rasmusson and Carpenter 1982; Pan and Oort 1983). Such a warming in the tropical Pacific and, to a lesser extent, in the other oceans was observed during the late 1970s (Graham 1994; Zhang et al. 1997). To illustrate the decadal variability of tropical SST, the expansion coefficient of the first EOF of SST within the domain 30°S–30°N is shown in Fig. 1a (thin line). The first EOF itself explains 29% of the total variability and is very similar to the leading principal component depicted in Zhang et al. [1997, their Fig. 3 (bottom)]. It is positive almost everywhere over the tropical oceans with a maximum in the central and eastern Pacific. It is evident from Fig. 1a that in 1977–94 the expansion coefficient is conspicuously large. The contribution of the first EOF to the tropical SST anomaly in 1977–88 is equal to 0.61. So it is probable that a large part of anomalies of 1977–88 could be induced by SST anomalies.

To test this hypothesis, numerical experiments were carried out using the AGCM of the Institute of Numerical Mathematics. It is a finite-difference model, with a horizontal resolution of $4^\circ \times 5^\circ$ in latitude and longitude and 21 σ levels in the vertical extending from 10 mb to the surface. The primitive equations are solved using the Arakawa C-grid (Arakawa and Lamb 1981) and a semi-implicit time integration scheme. The model contains a complete set of physical parametrizations: convection and condensation (Betts and Miller 1984), gravity wave drag (Palmer et al. 1986), horizontal and vertical diffusion, surface processes, and radiation.

All the model runs were carried out in the perpetual January mode. They were each of 27 months’ duration and started from a single state that was a realization of the model’s January climate. Two runs were performed: one using the SST distribution of 1946–76 and the other using that of 1977–88. SST was changed everywhere. There was no attempt to separate the impact of tropical and midlatitude SST anomalies. The sea ice distribution was not changed.

To estimate the statistical significance of the model response, one must know the dispersion of the 27-month average temperature and SLP fields for the AGCM. This dispersion can be known only after performing an ensemble of 27-month runs or one very long run. But we
Fig. 3. The EOFs of monthly mean SLP in the Northern Hemisphere, arbitrary units: (a) EOF-1 for the observations, 23% of dispersion; (b) EOF-2 for the observations, 12% of dispersion; (c) EOF-1 for the model, 25% of dispersion; (d) EOF-2 for the model, 14% of dispersion.
Fig. 4. The anomalies of 1977–88 relative to 1946–76: (a) temperature, K; (b) SLP, mb; anomalies of 1989–94 relative to 1977–88: (c) temperature, K; (d) SLP, mb.
can estimate the dispersion of 27-month averages using only two 27-month runs by calculating the dispersion of monthly mean values and assuming that dispersion scales are proportional to $T^{-1}$, where $T$ is the averaging interval. Nitsche (1996) showed that it is nearly true for AGCM midlatitude variability if $T$ is greater than 1 month.

Now note that in the AGCM the root-mean-square (rms) amplitude of monthly mean temperature in midlatitudes of the winter hemisphere is on the order of 3 K or less, and that of SLP is on the order of 6 mb or less. Then, 0.6 K and 1.2 mb are the estimates of the rms 27-month average temperature and SLP. If we define the response as significant if it exceeds two standard deviations, then 1.2 K and 2.4 mb will be the limits of statistical significance for temperature and SLP. Of course, more accurate criteria must depend on the dispersion at each grid point.

The observed SLP anomalies project strongly onto the first and second EOFs, so it is interesting to compare observed and model EOFs, shown in Fig. 3. One can see that model EOFs are not much different from the observed, both in the percentage of explained variance and in form.

In Figs. 5a and 5b one can see the model response for temperature and SLP. The model differences look like the observed ones (Figs. 4a,b). To be more specific, the model reproduces the warming of up to 2–3 K in Alaska and Canada and up to 2 K in western Siberia, and the cooling of up to 1 K over the southeastern United States. The only large discrepancy is model cooling in Europe of up to 2.5 K, which is much larger than the observed 0.5 K. The mean warming over the Northern Hemisphere continents in the model is equal to 0.27 K, not far from the observed value of 0.38 K. The SLP model differences are also not far from the observed; the main feature in the model response is the model decrease in the North Pacific of up to 5 mb, but the maximum SLP decrease is located somewhat northwest of its counterpart in the observations. The contributions of the first and the second AGCM EOFs to the model response are 0.04 and 0.49, not far from the observed values of 0.00 and 0.61.

The dynamical mechanisms responsible for the midlatitude circulation response to tropical SST anomalies are not discussed here because many studies have been devoted to this, for example, Boer (1989), Fennessey et al. (1985), and Held et al. (1989).

To understand the role of SST anomalies in the generation of the anomalies observed in 1989–94, an additional AGCM run was performed with SST prescribed as observed in 1989–94. But in these years large anomalies in tropical SST were not observed, although in the midlatitudes they are as large as 1 K in some places, as shown in Fig. 4c.

In Figs. 5c and 5d the differences between the model runs with the SST of 1989–94 and that of 1977–88 are presented. It is seen that they are far from the observed differences in Figs. 4c and 4d. The zonal component of the run with the SLP anomaly is even opposite to the observed, with positive anomalies to the north of 60°N and negative ones to the south. Also, instead of observed warming at the Northern Hemisphere continents, there is weak (0.03 K) cooling in the AGCM. This means that it is improbable that the observed anomalies of 1989–94 could have been induced by the SST anomalies. They are either internal atmosphere fluctuations or the response to another forcing.

Lower stratospheric ozone depletion that occurred during this period (Logan 1994; Bojkov and Fioletov 1997) was considered as such a forcing. The AGCM runs with normal and 10% reduced ozone in the lower stratosphere in the 70–250-mb layer were performed in the same manner as the runs with different SST. A detailed description of these runs can be found in Volodin and Galin (1998). As follows from that study, the response of model dynamics to the ozone decrease is very similar to the observed anomalies of 1989–94. Only the model temperature and SLP response are presented in this paper (Fig. 6). One can see that the patterns of the model (Fig. 6b) and the observed (Fig. 4d) SL pipes are almost identical, but the amplitude of the model differences is about 70% of the observed. The contribution of the first and the second SLP EOFs to the AGCM response are 0.76 and 0.03, not far from the observed values of 0.82 and 0.12.

The mechanism of the AGCM response to the low stratosphere ozone depletion is discussed in detail in Volodin and Galin (1998). It can be summarized concisely as follows. The anomaly of radiation heating induced by the anomaly of ozone compensates by vertical movements in the low stratosphere and excites the first mode of midlatitude low-frequency variability that is the coupling mode of troposphere and stratosphere. This induces near-surface anomalies of dynamics. Dynamically induced near-surface temperature anomalies do not cancel perfectly, and this is the reason for global warming.

Model temperature response is presented in Fig. 6a. Main features of the observed temperature anomaly are reproduced: the warming in Europe and Siberia up to 3 K, and cooling in eastern Canada up to 2.5 K. But cooling in the central United States is overestimated, and the sign of the anomalies in polar Siberia is wrong. These shortcomings are the reasons for underestimation of integral warming at Northern Hemisphere continents: it equals 0.13 K for the AGCM instead of 0.34 K for the observations. Such a discrepancy, in spite of SLP anomalies were reproduced almost exactly can be explained by the fact that there is a difference between “climatic” observed and model temperature gradients, especially in longitude direction. So similar anomalies of $U$ wind can induce somewhat different near-surface temperature anomalies.
Fig. 5. The model differences between runs with SST of 1977–88 and that of 1946–76: (a) temperature, K; (b) SLP, mb; the model differences between runs with SST of 1989–94 and that of 1977–88: (c) temperature, K; (d) SLP, mb.
4. Conclusions and discussion

The observed anomalies of the atmospheric dynamics in 1977–94 can be represented as a first approximation as a sum of two components. The first component reached its maximum in 1977–88. Main features of these anomalies can be reproduced as the AGCM response to the observed SST anomalies. The second component reached its maximum in 1989–94. It is little probable that the anomalies of 1989–94 are generated by SST anomalies, because main features of the AGCM response to SST anomalies of 1989–94 are even opposite to the observations. But main features of the observed anomalies can be obtained as the AGCM response to the observed ozone depletion in the low stratosphere.

The SLP anomalies of 1977–88 are closely correlated with the second EOF of monthly mean SLP, while the anomalies of 1989–94 are closely correlated with the first EOF. But the midlatitude atmospheric response to the tropical SST forcing and to the low-stratosphere ozone depletion are not necessarily exactly orthogonal in space and time domains. Hence the responses to these two forcings must not completely coincide with the first and the second EOFs. So, as is seen in Fig. 1b, some decreasing of the expansion coefficient of the second EOF was observed in 1989–94, while the tropical SST index does not decrease. Nevertheless we can say that the contribution of the first EOF to the SLP anomalies of 1989–94 and to the AGCM response to the ozone depletion is large, and the contribution of the second EOF to the SLP anomalies of 1977–88 and to AGCM response to tropical SST forcing is large.

Of course, such model runs cannot say anything about the nature of SST or ozone anomalies. The essence of these anomalies can be either internal SST and ozone fluctuations or coupled atmosphere–ocean and atmosphere–ozone fluctuations, or they can be induced by some third forcing of natural or anthropogenic origin. But the goal of this study is to show that main features of the anomalies of the observed circulation can be obtained as the AGCM response to the forcings that are external as regards the atmosphere.

Acknowledgments. The authors thank Prof. V. P. Dymnikov for useful discussions and comments and Prof. J. M. Wallace for critical remarks and polishing of the English syntax. This work was supported by Russian Fund of Basic Researches, Grants 96-05-64898 and 96-05-64487.

REFERENCES
Betts, A. K., and P. J. Miller, 1984: A new convective adjustment
scheme. ECMWF Tech. Rep. 43, 68 pp. [Available from
European Centre for Medium-Range Weather Forecasts, Shinfield
Park, Reading, Berkshire RG2 9AX, United Kingdom.]

Blackmon, M. L., 1976: A climatological spectral study of the 500
mb geopotential height of the Northern Hemisphere. J. Atmos.
Sci., 33, 1607–1623.

Boer, G. J., 1989: Concerning the response of the atmosphere to a
tropical sea surface temperature anomaly. J. Atmos. Sci., 46,
1898–1921.

Bojkov, R., and V. Fioletov, 1997: Changes of the lower stratospheric
ozone over Europe and Canada. J. Geophys. Res., 102(D), 1337–
1347.

Fennessy, M. J., M. J. L. Marx, and J. Shukla, 1985: General cir-
culation model sensitivity to 1982–83 equatorial Pacific sea sur-

Graham, N. E., 1994: Decadal-scale climate variability in the tropical
and North Pacific during the 1970’s and 1980’s: Observations
and model results. Climate Dyn., 10, 135–162.

Held, I. M. S., W. Lyons, and S. Nigam, 1989: Transients and the

Houghton, J. T., L. G. Meira Filho, B. A. Callander, N. Harris, A.
Kattenberg, and K. Maskell, Eds., 1995: Climate Change 1995:
The Science of Climate Change. Cambridge University Press,
339 pp.

Jones, P. D., S. C. B. Raper, R. S. Bradley, H. F. Diaz, P. M. Kelly,
and T. M. L. Wigley, 1986a: Northern Hemisphere surface air
25, 161–179.

—— ———, ——— ———, and ———, 1986b: Southern Hemisphere

25 585.

Mitchell, J. F. B., R. A. Davis, W. J. Ingram, and C. A. Senior, 1995:
On surface temperature, greenhouse gases, and aerosols: Models
and observations. J. Climate, 8, 2364–2386.

Nitsche, G., 1996: Some aspects of planetary-scale atmospheric var-
iability in a low-resolution general circulation model. Ph.D. dis-
sertation. University of Washington, 207 pp. [Available from
Dept. of Atmospheric Sciences, University of Washington, Box
351640, Seattle, WA 98195-1640.]

systematic westerly bias in general circulation and numerical
weather prediction models through an orographic gravity wave
1031.

Pan, Y. H., and A. H. Oort, 1983: Global climate variations connected
with sea surface temperature anomalies in the eastern equatorial
Pacific Ocean for the 1958–73 period. Mon. Wea. Rev., 111,
1244–1258.

Parker, D. E., P. D. Jones, C. K. Folland, and A. Bevan, 1994: In-
terdecadal changes of surface temperature since the late nine-

sea surface temperature and surface wind fields associated with
384.

Santer, B. D., K. E. Taylor, T. M. L. Wigley, J. E. Penner, P. D. Jones,
and U. Cubasch, 1995: Towards the detection and attribution of
an anthropogenic effect on climate. Climate Dyn., 12, 77–100.

Taylor, K. E., and J. E. Penner, 1994: Response of the climate system
to atmospheric aerosols and greenhouse gases. Nature, 369, 734–
737.

northern hemisphere winter circulation to ozone depletion in the

Wallace, J. M., Y. Zhang, and L. Bajuk, 1996: Interpretation of in-
terdecadal trends in the Northern Hemisphere surface air tem-
perature. J. Climate, 9, 249–259.

Zhang, Y., J. M. Wallace, and D. S. Battisti, 1997: ENSO-like in-