ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2008, Vol. 44, No. 5, pp. 594–605. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © E.A. Jadin, Yu.A. Zyulyaeva, E.M. Volodin, 2008, published in Izvestiya AN. Fizika Atmosfery i Okeana, 2008, Vol. 44, No. 5, pp. 641–653.

Relationships between Interannual Variations in Stratospheric Warmings, Tropospheric Circulation, and Sea Surface Temperature in the Northern Hemisphere

E. A. Jadin[a], Yu. A. Zyulyaeva[a], and E. M. Volodin[b]

[a] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Nakhimovskii pr. 36, Moscow, 117997 Russia*
e-mail: ejadin@yandex.ru

[b] *Institute of Numerical Mathematics, Russian Academy of Sciences, ul. Gubkina 8, Moscow, 119991 Russia*
e-mail: volodin@inm.ras.ru

Received May 19, 2006; in final form, March 24, 2008

Abstract—The leading modes of interannual and long-term variations in the stratospheric and tropospheric circulation and total ozone (TOMS data) and their relations to Northern Hemisphere sea surface temperature (SST) anomalies are investigated using the monthly mean NCEP/NCAR reanalysis data for the winter months of 1958–2003. Strong correlations are indicated between the interannual total ozone variations over Labrador and the North Atlantic and changes in the stratospheric polar vortex. The onset of major stratospheric warmings is connected not only with the strengthening of westerlies at the 500-hPa level in the midlatitude Atlantic, but also with the weakening of tropospheric winds over the north of eastern Siberia and strengthening over the Far East. In years with major stratospheric warmings, abnormally cold winters are observed in Eurasia, especially in eastern Siberia and northeastern China. The calculated simultaneous (with no time lags) correlations of the stratospheric circulation changes with El Niño/La Niña events give evidence of low correlations between the tropical Pacific SST anomalies and the stratospheric dynamics in the Arctic. However, there are high correlations of the extratropical Pacific and Atlantic SST anomalies with interannual tropospheric and stratospheric circulation variations, the stratospheric dynamics being more strongly connected with Pacific SST than with Atlantic SST anomalies. The interannual changes in tropospheric circulation are coupled to SST anomalies in both the Pacific and the Atlantic. Mechanisms of long-term changes in the interactive ocean–atmosphere–ozone layer system are discussed.

DOI: 10.1134/S0001433808050058

INTRODUCTION

The problem of climate and ozone layer changes is closely linked to the long-term changes (on time scales of about ten years or more) in the interactive ocean–atmosphere system. Global warming and ozone layer depletion are caused not only by greenhouse gas and freon increases in the atmosphere. An important role in the observed climate and ozone layer changes is played by natural long-term changes in the ocean and atmosphere [1].

The long-term changes in the ocean and atmosphere have been the objective of a number of studies. We mainly discuss only some results concerning the extratropical changes during the Northern Hemisphere winter. Teleconnections of the tropospheric geopotential are well known: the Pacific–North American (PNA) pattern, the North Atlantic Oscillation (NAO), etc. [2]. These correlations of the midtropospheric geopotential have a rather definite spatial structure and are related to the propagation of Rossby waves in the troposphere.

Trenberth [3] showed that sea-level pressure averaged over the Aleutian Low region had a completely different regime (~2-hPa decrease) in the winter seasons (November to March) of 1976–1988 than in the previous years (1946–1975). These long-term pressure changes correlate well with the PNA index, and the pattern of correlations with tropospheric parameters in this region agrees with the PNA pattern of the 500-hPa geopotential. The interannual changes in the atmospheric parameters are connected with the Pacific and Atlantic sea surface temperature variations, which also have a definite spatial pattern [4]; however, mechanisms whereby the long-term extratropical oceanic variations affect the atmospheric circulation are still unknown [5].

Teleconnections of European and Russian climate with interannual Atlantic SST variations have been discussed in numerous studies (e.g., [6, 7]). Analyzing SST variations for the winter seasons of 1900–1988, Deser and Blackmon [8] have shown that the first empirical orthogonal function (EOF) of Atlantic SST anomalies has a monopole spatial pattern with a center of action in the Gulf Stream region and that its coefficient exhibits secular changes with transition toward positive values after the 1940s. The second EOF of Atlantic SSTs has a dipole pattern with positive SST anomalies near Newfoundland and negative anomalies near the southeastern coast of the United States. Its coefficient experiences quasi-biennial (~2–2.5 years) and long-term changes (with a period of ~9 years in 1900–1944 and ~12 years in 1945–1988) with a strong negative trend after the 1940s. Temperature, sea-level pressure, and wind changes agree with the known mechanisms of the interaction with Atlantic SST anomalies.

In recent years, much attention has been given to the interaction between changes in natural climate and the ozone layer [1] and to stratosphere–troposphere coupling [9]. In particular, this is concerned with the results of studies of Thompson, Wallace, et al. [10, 11], where strong correlations were found between interannual and longer term extratropical sea-level pressure variations during the Northern Hemisphere winter (January–March) and Arctic stratospheric geopotential variations, which they called the Arctic Oscillation (AO). The AO index was defined as the interannual variations in the coefficient of the first EOF of sea-level pressure north of 20° N [10]. The regressions of the interannual changes in the geopotential of the lower (not middle) Arctic troposphere and stratosphere on the AO index have a nearly symmetric longitudinal pattern and resemble an analogous stratospheric pattern of the Southern Hemisphere (the Antarctic Oscillation, AAO) in September–November; hence, they were called "annular" modes [11]. Thus, apart from the well-known teleconnections of the tropospheric circulation [2], which are caused by the horizontal propagation of Rossby waves in the troposphere, there are strong correlations of troposphere–stratosphere coupling, which are due to the influence of the vertical propagation of planetary waves on the atmospheric circulation during the winter–spring period. Earlier, Baldwin et al. [12] discovered significant correlations between the interannual changes in the stratospheric polar vortex and the NAO, the index of which is determined as the difference in sea-level pressure between Iceland and the Azores. In the Atlantic sector, the spatial pattern of the AO is very similar to that of the NAO, as are the interannual variations in their indices [9]. The long-term changes in the AO index had a positive tendency after the late 1960s [11]; however, in the past decade, there has been a decrease in the AO index, which is difficult to understand from the standpoint of anthropogenic forcing of climate changes [13].

The causes of the Arctic and Antarctic Oscillations and their long-term changes are now extensively being discussed [14]. Possible causes may be the nonlinear interaction of dynamic atmospheric processes [15], increased anthropogenic emissions of greenhouse gases into the atmosphere [16], ozone layer depletion [17], and the influence of interannual and long-term Atlantic SST anomalies on atmospheric wave activity and the ozone layer [18, 19].

The aim of this study is to analyze interannual variations of stratospheric warmings occurrence and their relations to changes in the tropospheric circulation and SST anomalies in the winter period (December–March) and to develop a physical mechanism that could explain natural variability in the ocean–troposphere–stratosphere system on interannual and longer term time scales.

The data used for analysis were the monthly mean tropospheric and stratospheric zonal wind, surface temperature, and Pacific and Atlantic SST anomalies for each month (December–March) of 1958–2003 from the NCEP/NCAR reanalysis [20] and total ozone (TO) data (TOMS data for 1979–1992 and ground-based data [21]). In contrast to the commonly used geopotential data [2, 11], we consider zonal wind changes because they have more distinct nonzonal features during December–March. To remove seasonal variations, deviations (anomalies) from the average over the given period were calculated for each month. Since there is evidence of the enhancement of the coupling between the stratosphere and the troposphere in January–February [22], the emphasis was placed on analysis of midwinter data. The analysis was conducted by means of EOF expansion and singular value decomposition (SVD) of the fields considered. The SVD makes it possible to find modes of two time-varying fields that have the strongest nonlocal correlations [23].

INTERANNUAL CHANGES IN STRATOSPHERIC DYNAMICS AND TOTAL OZONE

The mechanism of stratospheric warmings is associated with the effect of quasi-stationary planetary waves on the stratospheric zonal circulation, as a result of which unusual changes in the potential stratospheric vortex occur [24]. During stratospheric warmings, planetary waves retard the westerlies in the Arctic stratosphere, induce strong downward motions, and lead to a warming, which can reach tens of degrees in a few days in the stratosphere. One of the necessary conditions for stratospheric warmings is the focusing of planetary waves into the polar stratosphere [25], which depends on the zonal displacement of the line between westerly and easterly winds (critical line) in the equatorial stratosphere [26, 27]. Note that, in spite of much research [9, 28], the causes of interannual variations of stratospheric warmings occurrence are still unknown.

Figure 1 shows the first and second EOFs of the 30-hPa zonal wind anomalies in January 1958–2003, expressed as correlations (in %) of wind anomalies at each grid point with interannual variations of their coefficients. Shaded areas show statistically signifi-

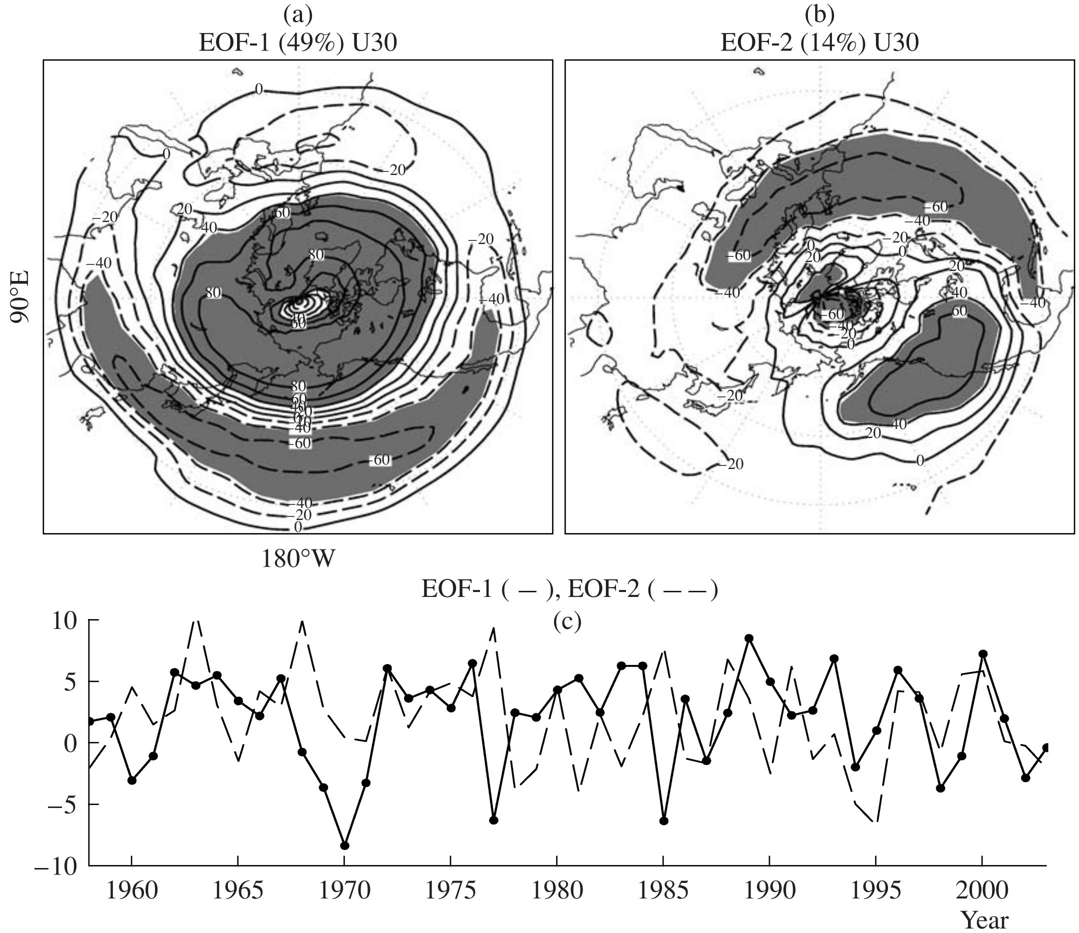

Fig. 1. (a) First and (b) second EOFs of the anomalies of zonal wind at 30 hPa in January 1958–2003 expressed as the correlations (in %) of wind anomalies at each grid point with interannual changes in the expansion coefficients (in arbitrary units). Hereafter, the correlations statistically significant at 95% are shaded. (c) The solid line shows the coefficient of the first EOF, and the dashed line is the coefficient of the second EOF.

cant correlations (at a 95% significance level). For other winter months, the correlation pattern is analogous, except that interannual changes in the expansion coefficient differ from the January ones. To find out how the January fields for each year vary, the EOF coefficient for a given year (in arbitrary units) should be multiplied by the spatial pattern of correlations. The contribution of the first EOF to the total variance is 49% and that of the second EOF is 14%; that is, the first EOF is the leading mode of variability of stratospheric dynamics. Its spatial pattern shows changes of opposite sign (dipole) in zonal wind between the subtropics and the stratospheric Arctic vortex, which have a nearly zonally symmetric (annular) pattern. The major stratospheric warmings in January 1960, 1970, 1977, 1985, 1987, 1994, 1998, and 2002 are associated with the minima of the first EOF coefficient, during which a deceleration (easterly anomalies) of the zonal wind in the Arctic stratosphere and the enhancement (westerly anomalies) of the subtropical jet, particularly over the Pacific, are observed. The maxima of the coefficient of the first EOF are associated with cold winters of the Arctic stratosphere, which have become more frequent since the mid-1980s [28].

Despite the smaller contribution of the second EOF to the total variance, it is important for stratospheric circulation changes in some years. The pattern of the second EOF is characterized by two opposite changes in the zonal wind over the Atlantic, Europe, and the United States, which are associated with a stratospheric anticyclone and cyclone, respectively, in years with stratospheric warmings. The contribution of the second EOF is most pronounced during the major stratospheric warmings in January 1977 and 1985 (positive peaks of the second EOF coefficient). In these years, the contributions of the first and second EOFs over the west coast of the United States are added, which results in very strong stratospheric warmings. Note that changes in the coefficient of the second EOF have a negative tendency after the mid-1970s.

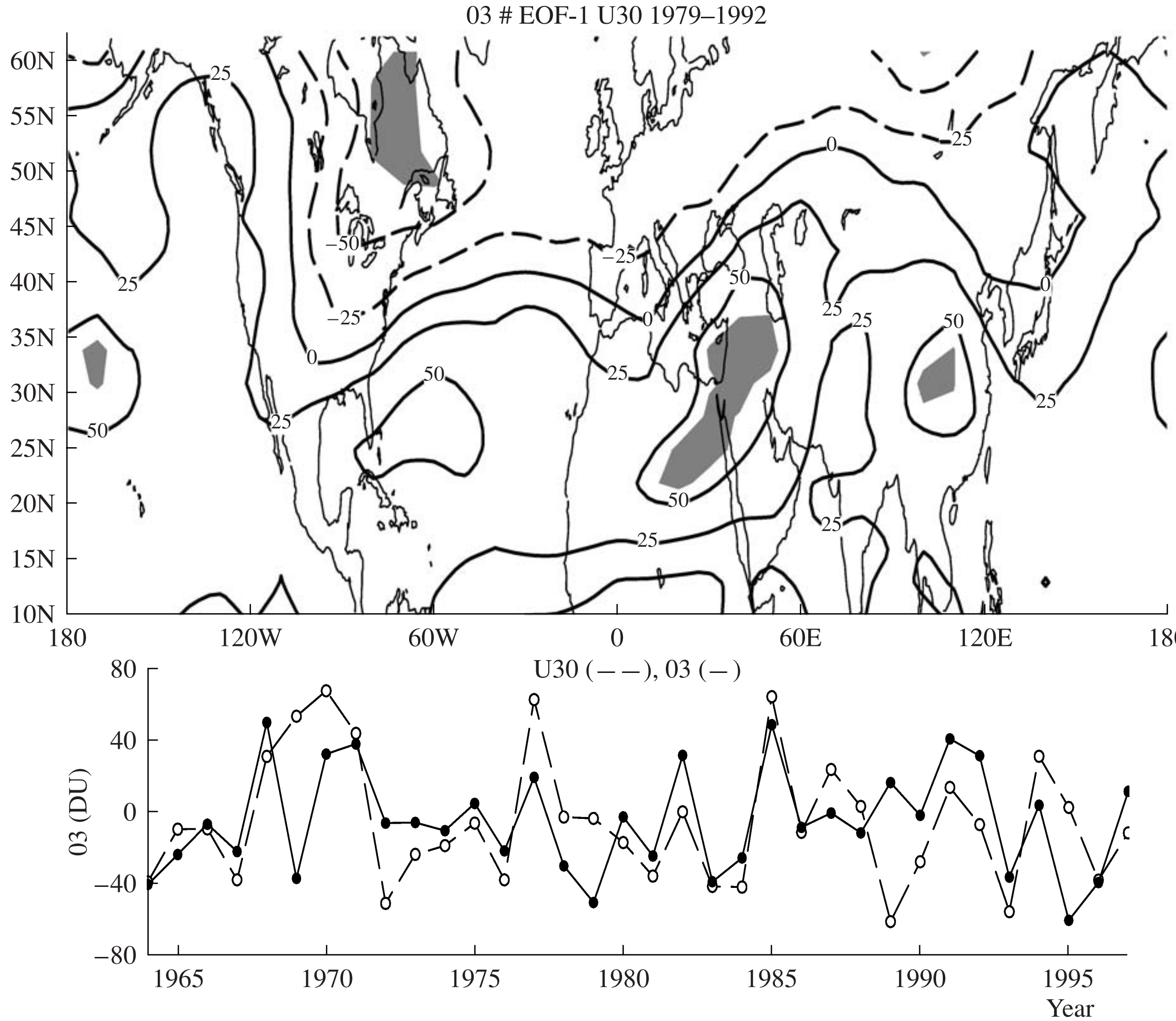

Fig. 2. (top) Correlations (in %) of total ozone anomalies in January 1979–1992 with interannual changes in the coefficient of the first EOF of zonal wind anomalies at 30 hPA. (bottom) Ozone anomalies (DU) at Goose Bay (53° N, 60° W) (solid line) and anomalies of zonal wind at 30 hPa (–2 m/s) at 80° N, 130° W (dashed line) in January 1964–1997.

Quasi-decadal changes are observed in total ozone variations as well, because the long-term stratospheric circulation changes play an important role in the variability of the ozone layer [1]. Figure 2 shows correlations of TO anomalies with interannual changes in the coefficient of the first EOF of 30-hPa zonal wind anomalies in January 1979–1992 and the anomalies of ozone at the ozonometric station of Goose Bay (60° W, 53° N) and zonal wind (with the opposite sign) in the Canadian Arctic (130° W, 80° N), where connections of the stratospheric polar vortex with TO changes at Goose Bay are most pronounced [18].

The stratospheric warmings are associated not only with a temperature increase and the weakening of westerlies or even the reversal to easterlies, but also with a TO increase over the North Atlantic. Indeed, the TO was abnormally high in the Canadian Arctic during major stratospheric warmings in January 1970, 1977, and 1985 (negative minima of the first EOF coefficient; Fig. 1), with large longitudinal differences between TO variations. The largest TO increase was observed in the Labrador region, while at the Pacific coast of Canada, on the contrary, there was some TO decrease. In years with stratospheric warmings, a stratospheric anticyclone forms over the north of eastern Siberia and Canada, and air with high ozone concentrations is transported from the Chukchi Peninsula into the Labrador area, with a simultaneous ozone decrease over the Pacific coast of Canada owing to the inflow of air with small ozone amounts from the low-latitude Pacific [29]. The TO increase at Goose Bay during stratospheric warmings is also observed during the longer 1964–1997 period (Fig. 2), as in 1980–2004 (not shown). The unusual period from the mid-1970s to the early 1990s is distinguished from the other decades by the strongest connections of the TO

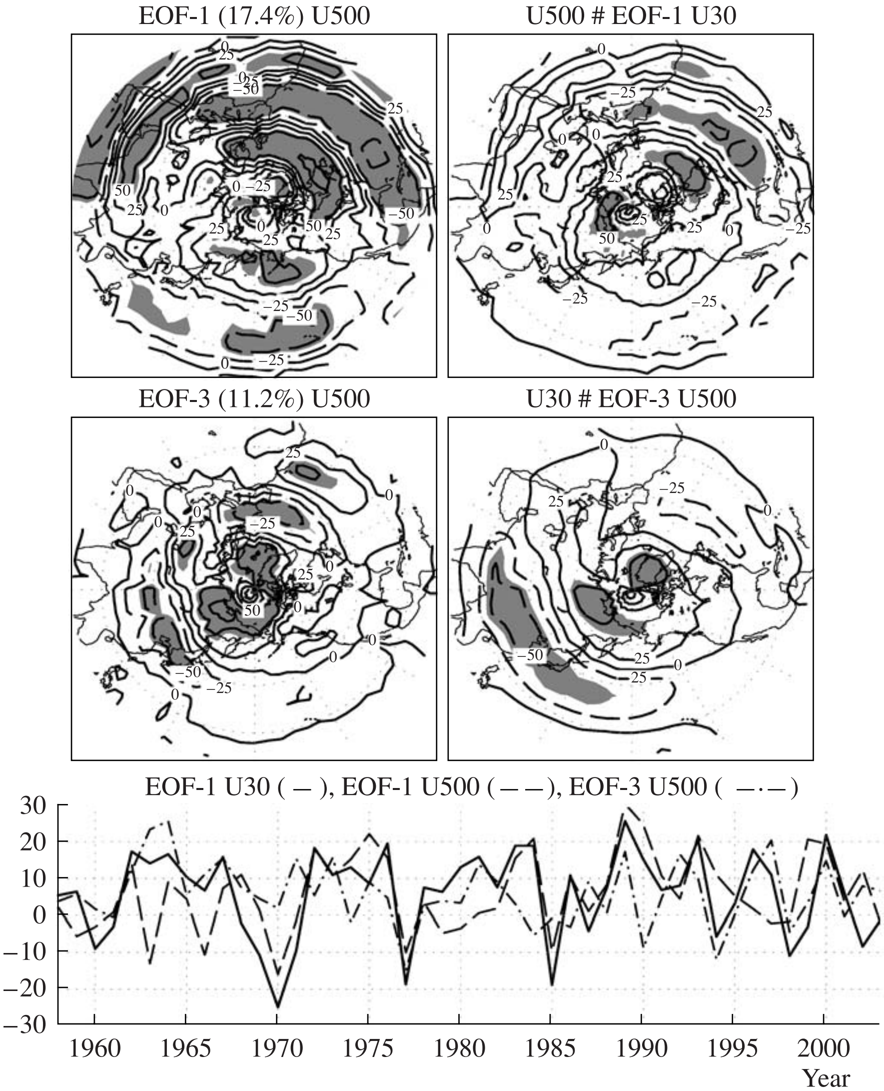

Fig. 3. First and third EOFs of zonal wind anomalies at 500 hPa (left panel) and correlations (%) of wind at 500 hPa at each grid point with the coefficient of the first EOF of wind anomalies at 30 hPa (solid line at the bottom), and of wind anomalies at 30 hPa (right panel) with variations in the coefficient of the third EOF of wind at 500 hPa (dot-and-dash line at the bottom). The dashed line shows the coefficient of the first EOF of wind at 500 hPa in January 1958–2003. Units are arbitrary.

variations with the Arctic stratospheric dynamics. Thus, the TO changes provide evidence of a variety of quasi-decadal periods in the long-term variability of stratospheric circulation and the related ozone layer changes.

STRATOSPHERE–TROPOSPHERE COUPLING

The problem of the interaction of stratospheric and tropospheric dynamics has been discussed extensively in recent years [9], when it has become clear that the variability of the stratospheric circulation and ozone layer depends not only on the interannual and longer term changes in quasi-stationary planetary waves propagating from the troposphere, but variations in stratospheric parameters can also affect the troposphere [30]. Therefore, it is important to investigate the dynamic coupling between the stratosphere and the troposphere.

The first (17.4% of the contribution to the total variance) and third (11.2%) EOFs of 500-hPa midtropospheric zonal wind anomalies and their coefficients for January 1958–2003 are shown in Fig. 3. Analysis has shown that these modes of tropospheric dynamics are related to stratospheric circulation changes and stratospheric warmings. The second EOF (12.2%) is weakly connected with stratospheric warmings. Indeed, interannual changes in the coefficients of the first EOFs of wind anomalies at 30 and 500 hPa have a similar time behavior. The major stratospheric warmings of 1970, 1977, and 1985 correspond to the main feature of the pattern of the first EOF, dipole oscillations (westerly wind anomalies at middle latitudes and easterly anomalies at high latitudes in the Atlantic), which agree with a negative phase of the NAO. However, it can be seen from Fig. 3 that similar 500-hPa zonal wind variations were also present in January 1963 and 1966, but no strong stratospheric warmings were observed. On the other hand, the warmings of 1994 and 2002 are not coupled to the minima of the coefficient of the first EOF of the 500-hPa wind.

Major differences between the patterns of the first EOF of tropospheric circulation and correlations of the 500-hPa wind with the coefficient of the first EOF of stratospheric circulation take place over northern Siberia. It is in this region that the third EOF of midtropospheric zonal wind anomalies makes the largest contribution to stratosphere–troposphere coupling. The absence of stratospheric warmings in January 1963 and 1966 can be explained by a contribution from the third EOF in this region, where large westerly anomalies of the 500-hPa wind were observed over northern Siberia and easterly anomalies were observed over China. Usually during major stratospheric warmings in 1977, 1985, 1994, and 1998, the third EOF describes the opposite situation in these regions: easterly 500-hPa wind anomalies over northern Siberia and westerly anomalies over China.

The onset of stratospheric warmings requires not only the presence of a strong tropospheric anticyclone over the Atlantic (blocking), but also the presence of easterly anomalies of zonal wind over northern Siberia, which was noted by Baldwin et al. [12], who found strong connections of zonal-mean atmospheric circulation with changes in the cross-polar index (500-hPa geopotential difference between 80° W, 62° N and 100° E, 58° N), which includes variations in tropospheric parameters over northern Siberia, associated with the third EOF of the zonal wind at 500 hPa (Fig. 3).

Are there any connections between stratospheric circulation changes and surface-temperature variations? The answer to this question is of practical importance for the long-term prediction of abnormally cold (warm) winters from stratospheric predictors [31–33]. Figure 4 shows the first SVD modes of the relations between the 30-hPa zonal wind, 500-hPa wind, and surface temperature anomalies in January 1958–2003. They are expressed as the correlations of the coefficient of the first SVD mode of the 30-hPa wind with the 500-hPa wind field and surface temperature anomalies at each grid point. The contribution of the mode to the total variance is var = 15% for wind anomalies and var = 16% for temperature anomalies, and their contribution to the total covariance is SCF = 75% [2, 3].

Apart from the well-known features of stratosphere–troposphere coupling [9], an important characteristic of the behavior of tropospheric dynamics is that two anticyclones appear in the polar troposphere during stratospheric warmings, one over northern Canada and the other over northern Siberia. This results in the transport of cold air masses from the Arctic to northern Europe and into the regions of eastern Siberia and northeastern China [34]. In contrast, the flow of warm air from the Atlantic produces a warming in the Labrador region during stratospheric warmings. Note that the pattern of the first SVD mode of relations between lower stratospheric and midtropospheric circulations (Fig. 4a) resembles the first EOF of the 500-hPa wind, but with elements of the third EOF (Fig. 3).

SST ANOMALIES AND THEIR CONNECTIONS WITH ATMOSPHERIC CHANGES

Ocean–atmosphere interaction has been discussed for years, but there is still no clear idea in understanding the mechanisms of the ocean influence on the atmosphere on quasi-decadal and longer scales. In this study, we consider relations between the stratospheric warmings occurrence and the SST anomalies during the Northern Hemisphere winter.

El Niño events are the most remarkable phenomena in the interacting ocean–atmosphere system that can have influence on the stratosphere [5]. However, our analysis has shown that there are no significant connections of the Southern Oscillation Index, defined as the Pacific SST anomalies in the Niño 3 region (5° N–5° S, 170°–120° W), with changes in the Northern Hemisphere extratropical stratospheric dynamics. The main features of the correlations of the Southern Oscillation Index with stratospheric zonal wind variations resemble the pattern of the second EOF of the lower stratosphere zonal wind (Fig. 1), but with smaller correlations, which do not exceed 30–40%. There are no strong connections of El Niño/La Niña events with changes in the stratospheric polar night jet and the Arctic Oscillation annular mode, in some contradiction with the results presented in [34]. This does not mean that the El Niño/La Niña events have no influence on the stratospheric circulation and ozone layer, because they have a long-term "memory" [35] and can lead to extratropical SST variations in both the Northern and Southern hemispheres a few years after their emergence. Therefore, it is necessary to investigate connections of extratropical SST anomalies with interannual and quasi-decadal changes in the stratospheric and tropospheric circulation.

Earlier, strong correlations were found between interannual variations in the stratospheric vortex of the Arctic and Antarctic and the ozone content at high latitudes of the Northern and Southern hemispheres

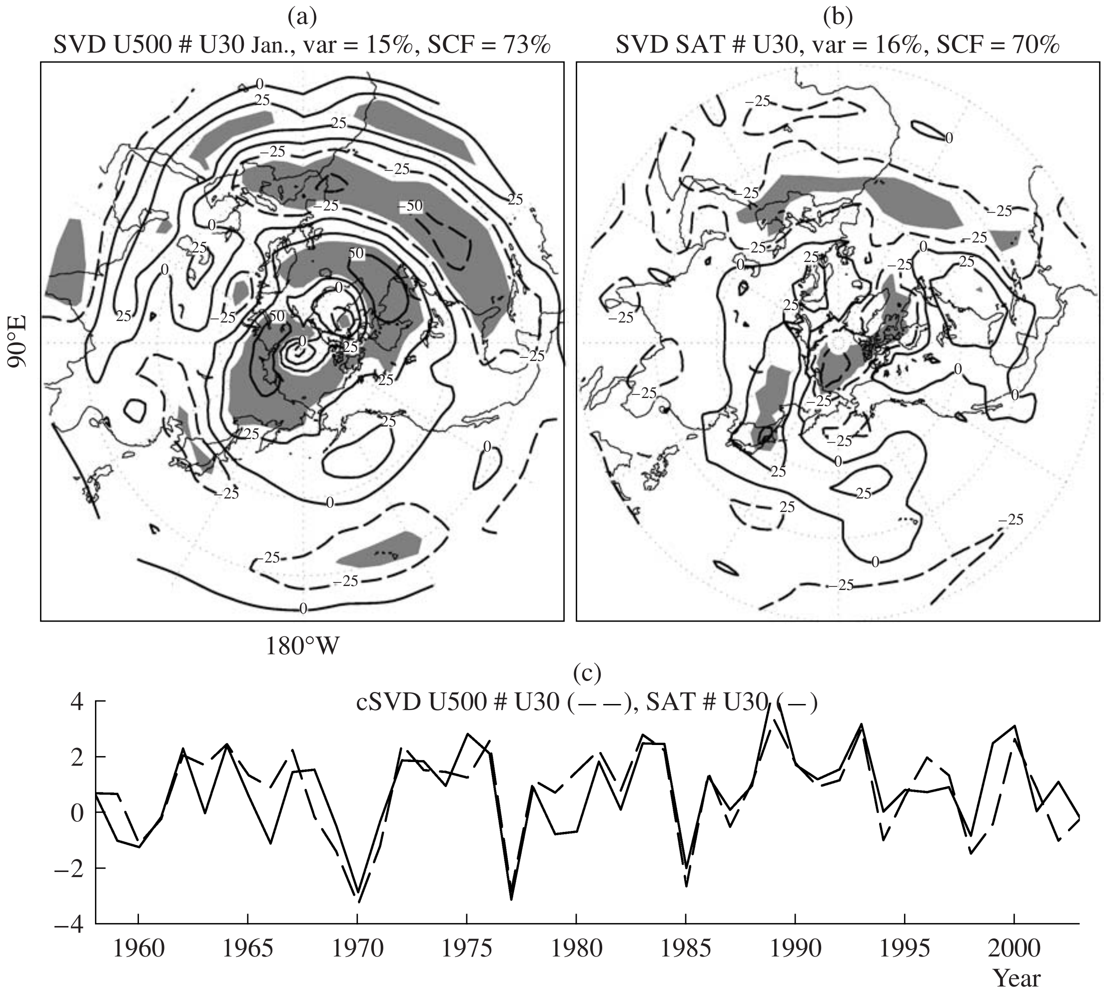

Fig. 4. (a) Correlations (%) of zonal wind at 500 hPa at each grid point with the coefficient of the first SVD mode of the relations between these anomalies and the anomalies of zonal wind at 30 hPa. (b) The same for the relations between the anomalies of surface air temperature (SAT) and zonal wind at 30 hPa. (c) Interannual variations in the coefficients of the first SVD modes of the relations of surface temperature (solid line) and the zonal wind at 500 hPa (dashed) with wind anomalies at 30 hPa in January 1958–2003. Units are arbitrary.

and the dipole pattern of SST anomalies (dipole across the Rockies in the Northern Hemisphere and the SST dipole across the Andes in the Southern Hemisphere) for 1979–1992 [1, 18]. A physical mechanism of these correlations is probably the interference of the orographic source and the thermal source (depending on the Pacific and Atlantic SST anomalies) that excite stationary planetary waves. The result of interference depends on the shifts in SST anomalies and is most clearly defined in the stratosphere. To verify this hypothesis, EOF and SVD analyses of the connections between the atmospheric circulation and extratropical Pacific and Atlantic SST anomalies north of 12.5° N were conducted for the winter months of 1958–2003.

Figure 5 shows the first two EOFs of the coupled Pacific and Atlantic SST anomalies (January) and their coefficients of coupled as well as separate anomalies for the Pacific and Atlantic. The pattern of the first EOF (16.6% of variance) of the coupled anomalies includes the pattern of the second EOF (18.6%) of SST anomalies separately for the Pacific with the centers of action in the Kuroshio region and anomalies of the opposite sign in the central and northern Pacific, while in the Atlantic it reproduces the well-known tripolar pattern of the first EOF (25.8%) of SST anomalies separately for the Atlantic [4, 8]. From Fig. 5, it follows that there was an abrupt transition of SSTs in the Atlantic to the new quasi-decadal regime in the early 1980s, which ended in the mid-1990s.

Analysis of SST anomalies has shown that this transition is most pronounced in the Labrador Current region in the center of action at 50° W, 57.5° N. This is illustrated in Fig. 6, where SSTs averaged for November to December and for January to February 1958–2003 are shown at this point. There are large differences in SST changes in this Atlantic region between

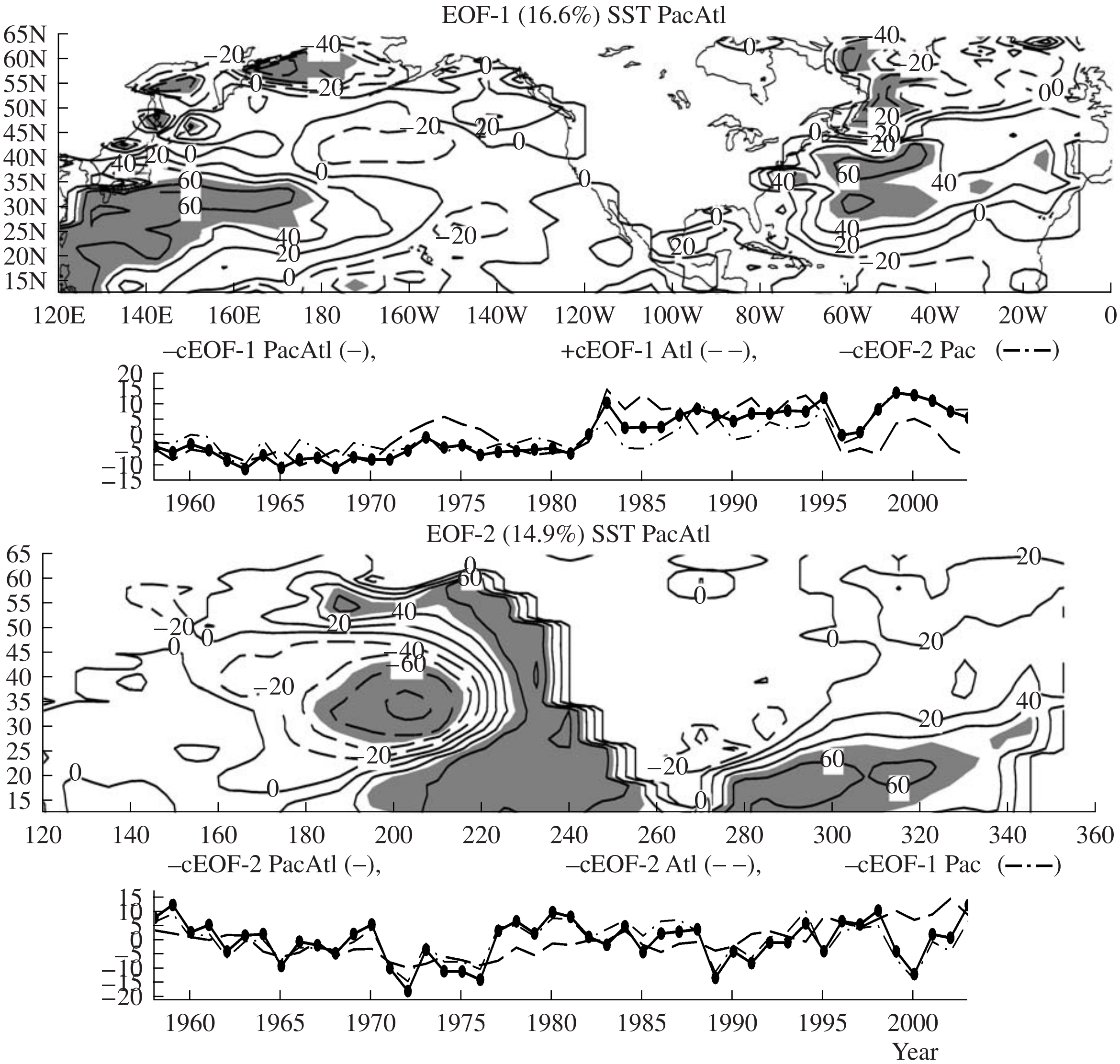

Fig. 5. First and second EOFs of coupled SST anomalies in the Pacific and Atlantic and their coefficients (solid curves). The dashed and dot-and-dash lines show the EOF coefficients of SST anomalies separately for the Atlantic and Pacific, respectively.

the start and the middle of winter. Peng and Fyfe [36] have also shown that there are large discrepancies in the spatial pattern of interannual sea-level pressure variations for the early and middle winter, depending on SST anomalies in the region 40°–60° W, 40°–50° N.

This can imply that the usual averaging of data over December–March (e.g., [8, 10]) may have a substantial disadvantage in studying the ocean–atmosphere interaction from the standpoint of the discrepancies of wave activity in early and late winter [22]. A sharp cooling of the Labrador SSTs occurred at the beginning of 1982, decreasing slowly for several years during the winter–spring period. In the Pacific, no sharp change was observed; rather, there was a trend of the coefficient of the second EOF of SST anomalies. It should be noted that the temporal behavior of the first EOF coefficient in the "calm" periods of 1958–1981 and 1996–2003 follows the behavior of the coefficient of the second EOF of the Pacific, but not during the "disturbed" 1982–1996 period.

The second EOF of the coupled SST anomalies consists of the first Pacific EOF with dipole-like changes in the central Pacific and along the North American coast and the second EOF of the Atlantic with a monopole pattern with the center of action in the southern Atlantic. The interannual and quasi-decadal variability of this mode of coupled anomalies almost exactly corresponds to changes in the first EOF of SSTs separately for the Pacific. Note that the behavior of the coefficient of the second EOF of the Atlantic also agrees with the long-term Pacific SST changes. The correspondence of the long-term SST changes in the Pacific and Atlantic requires an expla-

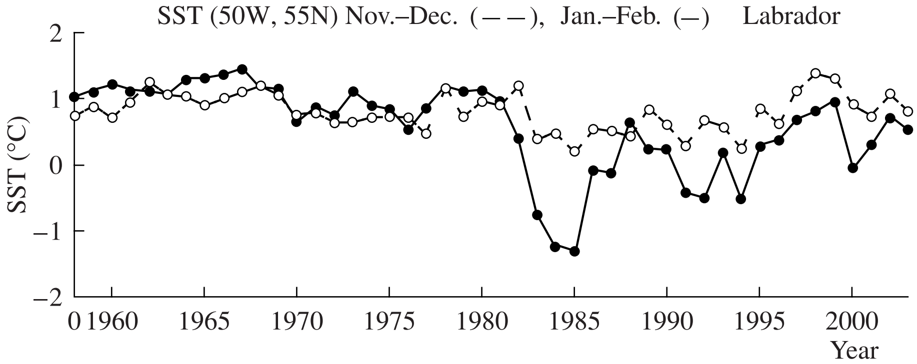

Fig. 6. Temperature changes (°C) at the surface of the Labrador Current at 57.5° N, 50° W averaged over November–December (dashed) and January–February (solid) in 1958–2003.

nation, possibly, through the influence of the atmosphere on oceanic variability.

Since there is strong evidence of the existence of quasi-decadal atmospheric regimes [3, 8], it is interesting to study how these atmospheric changes are related to interannual and long-term extratropical SST anomalies in the Pacific and Atlantic oceans. Figure 7 shows the SVD modes of the relations between the interannual coupled anomalies of SSTs and the zonal wind at 30 and 500 hPa for January 1958–2003. It can be seen that stratospheric and tropospheric circulations are associated with different modes of SST anomalies. The usual dipole changes in the lower stratosphere zonal wind between the subtropics and high latitudes correlate most strongly with SST anomalies in the Pacific and southern Atlantic, the features of which are similar to the second EOF of the coupled SST anomalies (Fig. 5). The SVD analysis of the relations between stratospheric dynamics and Atlantic SST anomalies revealed weak correlations (below 40%) of the lower stratosphere zonal wind, the pattern of which fits neither the first nor the second EOF of the stratospheric wind (Fig. 1). In contrast to the Atlantic, correlations of the interannual lower stratospheric variations with SST anomalies of the Pacific alone are strong and have a pattern similar to correlations of the coupled SST anomalies shown in Fig. 7.

Thus, the simultaneous (January to January) relations between the stratospheric dynamics and SST anomalies are stronger in the Pacific than in the Atlantic, except in its southwestern area. Although the coefficients of the first SVD modes of SST anomalies in the Pacific and Atlantic have similar tendencies, sharp changes in the coefficient of the Atlantic SSTs in 1983–1996 result in the loss of significant correlations between the Atlantic SST and stratospheric circulation. The correlations between the coefficients of the leading EOFs and SVD modes of both the coupled SST anomalies and SST anomalies separately for the Pacific and Atlantic in January 1958–2003 are presented in the table.

The pattern of correlations of SST anomalies with midtropospheric circulation changes is different from that for the stratospheric circulation, especially in the Atlantic. The first SVD mode of the correlations between the 500-hPa zonal wind and the coupled SST anomalies agrees with the pattern of the first EOF of the 500-hPa zonal wind (Fig. 4). Calculations of SVD modes of SST anomalies separately for the Pacific and Atlantic revealed similar patterns of the 500-hPa zonal wind with teleconnections like the PNA in the Pacific and the NAO in the Atlantic. The corresponding SVD modes of SST anomalies in the Pacific are similar in structure to those shown in Fig. 7 for the Pacific, while in the Atlantic they are similar to tripolar oscillations of the first EOF of Atlantic SST anomalies (Figs. 5, 7). The behavior of the SVD mode coefficient of the coupled SST anomalies is generally close to that of the coefficient of the SVD mode of the Pacific SSTs, as is the pattern for the stratospheric dynamics, but, in contrast to connections with the stratospheric dynamics, it is an average between the SST coefficients separately for the Pacific and Atlantic.

Thus, not only are differences present in the connections of the interannual stratospheric and tropospheric variations with SST anomalies (with dominant connections of the Pacific SSTs for the stratosphere and equivalent connections of the Pacific and Atlantic SSTs for the troposphere), but these connections experience disruptions during the disturbed 1983–1996 period. The causes of these disruptions are unknown and call for special studies.

DISCUSSION AND CONCLUDING REMARKS

The results of analysis provide evidence that different quasi-decadal periods are present in the interacting ocean–atmosphere–ozone layer system. The absence of well-pronounced trends in the lower stratosphere zonal circulation (Fig. 1) casts some doubt on the influence of ozone layer depletion on stratospheric dynamics because of radiative effects; rather, the

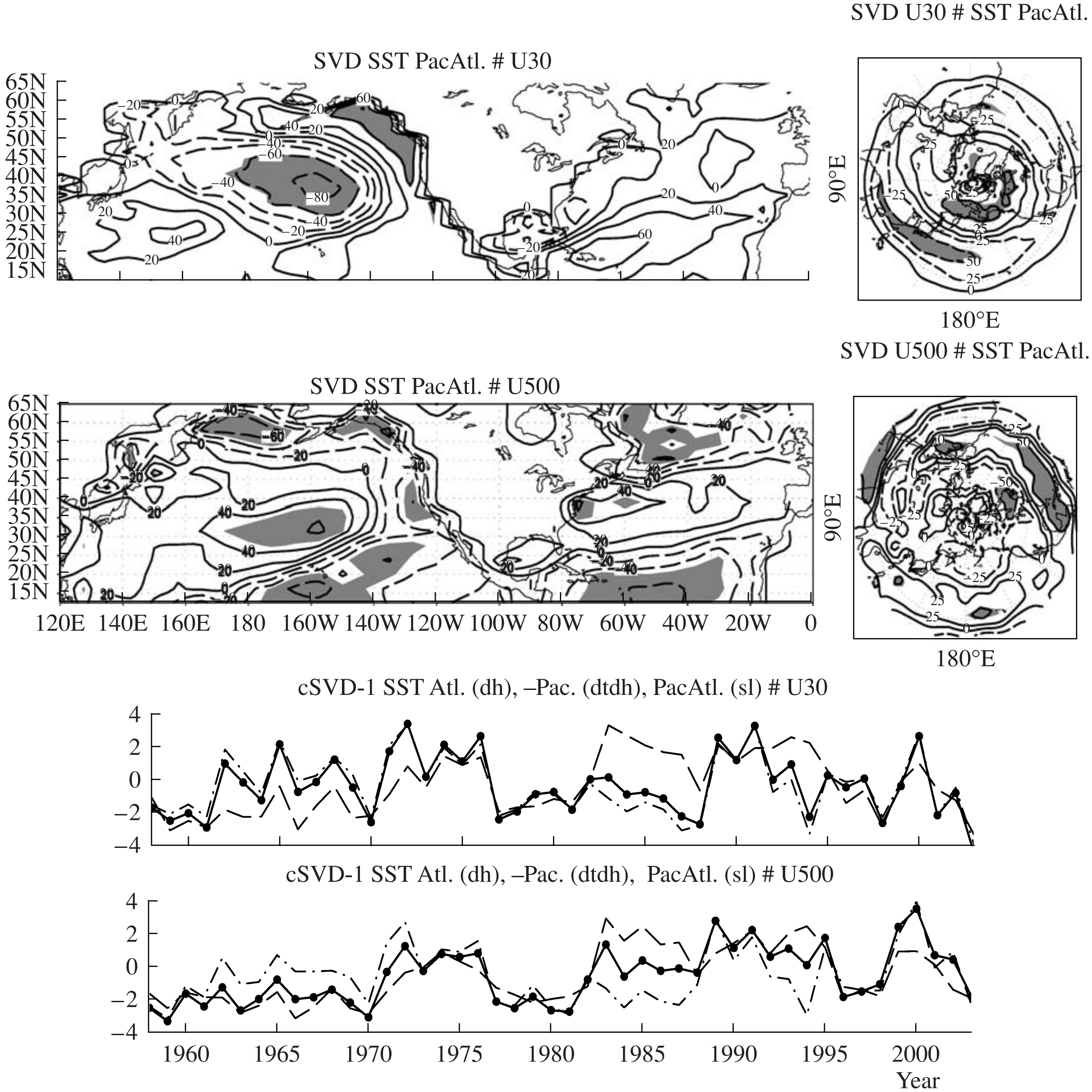

Fig. 7. First SVD modes of the relations between coupled anomalies of SST and the zonal wind at 30 and 500 hPa and their coefficients (solid lines). The dashed and dot-and-dash lines show the coefficients of the SVD modes of these relations for SST anomalies separately for the Atlantic and Pacific.

interannual and longer term variations in atmospheric wave activity affect ozone changes, including those in the ozone hole over Antarctica [1]. The unusual behavior of the ozone hole in 2002 is a remarkable example of the large role of stratospheric warmings in the variability of the ozone layer [37].

Note that analysis of the relations between the lower stratosphere zonal wind and SST anomalies for January 1979–1992 has shown the same pattern of Pacific and Atlantic SST anomalies as in [18], i.e., the pattern corresponding to a simple interference mechanism of the interaction of orographic and thermal sources of the excitation of stationary planetary waves with the centers of action of SSTs in the dipole across the Rockies. For 1958–2003, however, the pattern of correlations of SST anomalies most closely connected with the lower stratosphere dynamics is different from that presented in [18]. This can be due to the presence of various quasi-decadal periods and to intraseasonal differences in the ocean–atmosphere interaction between October–November and January–March [38]. Complicated problems of the ocean–atmosphere interaction and their link to stratosphere–troposphere coupling call for further investigation.

Correlations between coefficients of the EOF and SVD modes of coupled SST anomalies in the Pacific and Atlantic and the coefficients of the modes of SST anomalies separately for the Pacific and Atlantic

	EOF 1 Atl	EOF 2 Pac
EOF 1 PacAtl	–0.65	**0.88**
	EOF 2 Atl	EOF 1
EOF 2 PacAtl	0.40	**0.92**
	SVD Atl # U30	SVD Pac # U30
SVD PacAtl # U30	0.52	**–0.96**
	SVD Atl # U500	SVD Pac # U500
SVD PacAtl # U500	**0.79**	**–0.75**

Note: The underlined values are statistically significant at 99%.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, project no. 05-05-65289.

We thank the anonymous reviewers for helpful comments.

REFERENCES

1. E. A. Jadin, K. Ya. Kondratyev, V. I. Bekoryukov, and P. N. Vargin, "Influence of Atmospheric Circulation Variations on the Ozone Layer," Int. J. Remote Sensing **26**, 3467–3478 (2005).
2. J. M. Wallace and D. S. Gutzler, "Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter," Mon. Weather Rev. **109**, 784–812 (1981).
3. K. E. Trenberth, "Recent Observed Interdecadal Climate Changes in the Northern Hemisphere," Bull. Am. Meteorol. Soc. **71**, 988–993 (1990).
4. J. M. Wallace, C. Smith, and Q. Jiang, "Spatial Patterns of Atmosphere–Ocean Interaction in the Northern Winter," J. Clim. **3**, 990–998 (1990).
5. *CLIVAR, 1995. A Study of Climate Variability and Predictability,* (Science Plan. WCRP-89, WMO/TD, 1995), No. 690.
6. A. B. Polonsky and D. V. Basharin, "On the Influence of the North Atlantic and Southern Oscillations on the Variability of Air Temperature in the Mediterranean-European Region," Izv. Akad. Nauk, Fiz. Atmos. Okeana **38**, 135–145 (2002) [Izv., Atmos. Ocean. Phys. **38**, 119–128 (2002)].
7. S. K. Gulev, "Climate Variability of the Intensity of Synoptic Processes in the North Atlantic Midlatitudes," J. Clim. **10**, 574–592 (1997).
8. C. Deser and M. L. Blackmon, "Surface Climate Variations over the North Atlantic Ocean during Winter: 1900–1989," J. Clim. **6**, 1743–1753 (1993).
9. M. P. Baldwin, "The Arctic Oscillation and Its Role in Stratosphere–Troposphere Coupling," SPARC Newslett., No. 14, 10–14 (2000).
10. D. W. J. Thompson and J. M. Wallace, "The Arctic Oscillation Signature in the Wintertime Geopotential Height and Temperature Fields," Geophys. Res. Lett. **25**, 1297–1300 (1998).
11. D. W. J. Thompson, J. M. Wallace, and G. C. Hegerl, "Annular Modes in the Extratropical Circulation. Part II: Trends," J. Clim. **13**, 1018–1035 (2000).
12. M. P. Baldwin, X. Cheng, and T. J. Dunkerton, "Observed Correlations between Winter-Mean Tropospheric and Stratospheric Circulation Anomalies," Geophys. Res. Lett. **104**, 30 937–30 946 (1994).
13. J. E. Overland and M. Wang, "The Arctic Climate Paradox: The Recent Decrease of the Arctic Oscillation," Geophys. Res. Lett. **32**, 6701–6705 (2005).
14. J. M. Wallace, "North Atlantic Oscillation/Annular Mode: Two Paradigms - One Phenomenon," Q. J. R. Meteorol. Soc. **126** (564), 791–805 (2000).
15. B. Christiansen, "Downward Propagation of Zonal Mean Zonal Wind Anomalies from the Stratosphere to the Troposphere: Model and Reanalysis," J. Geophys. Res. **106**, 27 307–27 332 (2001).
16. D. T. Shindell, "Northern Hemisphere Winter Climate Response to Greenhouse Gas, Ozone, Solar and Volcanic Forcing," SPARC Newslett., No. 17, 14–18 (2001).
17. E. M. Volodin and V. Ya. Galin, "Interpretation of Winter Warming on Northern Hemisphere Continents in 1977–94," J. Clim. **12**, 2947–2955 (1999).
18. E. A. Jadin, "Arctic Oscillation and Interannual Variations in the Sea Surface Temperature in the Atlantic and Pacific Oceans," Meteorol. Gidrol. **8**, 28–40 (2001).
19. A. W. Robertson, C. R. Mechoso, and Kim, Young-Joon, "The Influence of Atlantic Sea Surface Temperature Anomalies on the North Atlantic Oscillation," J. Clim. **13**, 122–138 (2000).
20. E. M. Kalnay, et al., "The NCEP/NCAR Reanalysis Project," Bull. Am. Meteorol. Soc. **77**, 437–471 (1996).
21. *Ozone Data for the World* (Atmospheric Environment Service, WMO, Toronto.
22. M. Honda, H. Nakamura, J. Ukita, et al., "Interannual Seesaw between the Aleutian and Icelandic Lows. Part I: Seasonal Dependence and Life Cycle," J. Clim. **14**, 1029–1042 (2001).
23. C. S. Bretherton, C. S. Smith, and J. M. Wallace, "An Intercomparison of Methods for Finding Coupled Patterns in Climate Data," J. Clim. **5**, 541–560 (1992).
24. M. E. McIntyre, "How Well Do We Understand the Dynamics of Stratospheric Warmings?" J. Meteorol. Soc. Jpn. **60**, 37–56 (1982).
25. K. Labitzke, "On the Interannual Variability of the Middle Stratosphere during the Northern Winters," J. Meteorol. Soc. Jpn. **60**, 124–139 (1982).

26. T. Dunkerton, C.-P. Hsu, and M. E. McIntyre, “Some Eulerian and Lagrangian Diagnostics for a Model of Stratospheric Warmings,” J. Atmos. Sci. **38**, 819–843 (1981).
27. E. A. Jadin and B. M. Kiryushov, “Resonance of Planetary Waves and Sudden Stratospheric Warmings,” Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana **24**, 34–41 (1988).
28. K. Labitzke and B. Naujokat, “The Lower Arctic Stratosphere in Winter since 1952,” SPARC Newslett., No. 15, 11–14 (2000).
29. E. A. Jadin, “On the Relations of Stratospheric Parameters to Surface Temperature Anomalies,” Meteorol. Gidrol. **6**, 27–37 (2006).
30. M. P. Baldwin and T. J. Dunkerton, “Propagation of the Arctic Oscillation from the Stratosphere to the Troposphere,” J. Geophys. Res. **104**, 30 937–30 946 (1999).
31. D. W. J. Thompson, M. P. Baldwin, and J. M. Wallace, “Stratospheric Connection to Northern Hemisphere Wintertime Weather: Implications for Prediction,” J. Clim. **15**, 1421–1442 (2002).
32. M. P. Baldwin, “Weather from the Stratosphere,” Science **301**, 317–319 (2003).
33. E. A. Jadin, “Ozone and Variations in Surface Temperature,” Meteorol. Gidrol. **10**, 64–73 (2004).
34. W. Chen, M. Takahashi, and H.-F. Graf, “Interannual Variations of Stationary Planetary Wave Activity in the Northern Winter Troposphere and Their Relations to NAM and SST,” J. Geophys. Res. D **108**, 4797–4812 (2003).
35. G. A. Jacobs, H. E. Hurlburt, J. C. Kindle, et al., “Decade-Scale Trans-Pacific Propagation and Warming Effects of an El Niño Anomaly,” Nature **370**, 360–363 (1994).
36. S. Peng and J. Fyfe, “The Coupled Patterns between Sea Level Pressure and Sea Surface Temperature in the Midlatitude North Atlantic,” J. Clim. **9**, 1824–1839 (1996).
37. E. A. Zhadin and P. N. Vargin, “2002 Antarctic Ozone Hole,” Izv. Akad. Nauk, Fiz. Atmos. Okeana **40**, 786–795 (2004) [Izv., Atmos. Ocean. Phys. **40**, 704–712 (2004)].
38. A. Czaya and C. Frankignoul, “Observed Impact of Atlantic SST Anomalies on the North Atlantic Oscillation,” J. Clim. **15**, 606–623 (2002).