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An investigation of the separability of chemical and dynamic sources on ozone variations

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Abstract. Interannual variations of the monthly mean total ozone, stratospheric angular momentum and their interrelations are investigated by applying of the empirical orthogonal functions and singular value decomposition for October in the Southern Hemisphere (SH) and January in the Northern Hemisphere (NH) during 1979–1992. High correlations between interannual variations of the total ozone and stratospheric circulation in the mid to high latitudes of both hemispheres were obtained. On the basis of these relations, reconstruction of the total ozone changes was performed using the linear regression of observed total ozone in terms of the calculated stratospheric momentum variations. This allowed us to estimate in the first approximation a relative influence of "dynamical" and "chemical" impacts on observed ozone trends. The results show that largest "chemical" contributions to observed trends in the NH in January, which are not associated with the long-term changes of the stratospheric dynamics, take place over France, Germany, Italy (∼70%), eastern coast of the United States (∼70%), Moscow region (∼60%), Baikal, Far East, and Japan (∼50%). For the SH in October, those were found southeastward from Australia (up to 90%) and South America (∼70%). Large negative trends of the total ozone in the midlatitudes of the North Pacific in January are mainly caused by long-term changes of the stratospheric dynamics. Possible mechanisms of decadal variations in the coupled ocean-atmosphere system and their relation to interannual and decadal changes of the ozone layer are discussed.

1. Introduction

One of most important questions of the ozone layer problem is an ability to distinguish between the anthropogenic impacts on the ozone layer and its long-term natural changes. During recent years the confidence of many scientists on only the ecological nature of the ozone decrease is being replaced by an understanding of the large role of long-term natural processes in the observed ozone trends. Decadal variations in the coupled ocean-atmosphere system could result in the weakening of stratospheric wave activity in the middle and high latitudes during the past two decades, which created favorable conditions for the chemical destruction of ozone layer (strong isolation of the polar vortex, decrease of the eddy ozone and heat exchanges with midlatitudes, cooling of the lower stratosphere, formation of polar stratospheric clouds, etc.). Some evidence of decadal changes of the stratospheric and tropospheric circulation in the Southern Hemisphere (SH) has been presented by *Kawahira and Hirooka* [1992] and *Hurrell and van Loon* [1994]. These changes were beginning in June–August; therefore they were hardly caused by an influence of radiative budget changes on the stratospheric dynamics due to ozone reduction in September–November [*Van Loon and Tourpali,* 1995]; rather, interannual variations of the atmospheric wave activity are the primary cause of both the observed ozone and circulation changes. Confirmation of this point of view was provided by the analysis of the interannual variations of the zonal mean total ozone and stratospheric angular momentum (100–0.4 hPa) on the global scale in 1979–1992 [*Jadin,* 1996, 1999; *Jadin and Diansky,* 1996]. It was shown that the stratospheric zonal cir-

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culation underwent an abrupt transition to a new decadal regime in subtropics of the SH and Northern Hemisphere (NH) in the summer of 1980. This regime is characterized by the strengthening of positive (westerly) stratospheric momentum anomalies during wintertime after 1980, the anomalies propagating from subtropics to polar regions and resembling the V structure in low-frequency propagation of the atmospheric angular momentum [*Dickey et al.*, 1992]. Strong negative correlations between interannual variations of the total ozone and stratospheric momentum were found. These relations are most prominent between interannual variations of the stratospheric dynamics in the vicinity of the Antarctic polar vortex and the development of the ozone hole in the Antarctic during September–November, as well as at middle and high latitudes of the NH during January–March. It should be noted that this point of view does not contradict observations and chemical mechanisms of the ozone layer destruction. Moreover, this direction of investigations can provide a better understanding of the link between many unresolved questions of the ocean-atmosphere interaction and ozone changes on decadal timescales.

Interannual and decadal variations of the stratospheric wave activity are associated with changes of the planetary waves penetrating from the troposphere to the stratosphere during wintertime, which in turn depend on interannual variations of the sea surface temperature (SST) in the Pacific, Atlantic, and Indian Oceans because the thermal generation of stationary planetary waves is related to SST changes. On the one hand, it is well known that the wave forcing can result in large changes of transport processes and composition of the stratosphere. On the other hand, changes of ozone and other gases can modify the radiative regime, temperature gradients, stratospheric circulation and conditions for the wave propagation. Therefore, numerous feedbacks between variations of the ocean, atmospheric circulation and wave activity, and chemical composition result in large difficulties in the separation of anthropogenic and natural impacts on the ozone layer and climate changes. In fact, simulations with the help of the general circulation model including the chemistry, which would take into account long-term changes of the atmosphere caused by anthropogenic and natural influences, are needed for this purpose. The two- and three-dimensional stratospheric model predictions [*World Meteorological Organization*, 1998] do not simulate long-term natural changes of atmospheric circulation and wave activity. Therefore, it is not surprising that there are large uncertainties in predictions of the future recovery of the ozone layer [*Shindel et al.*, 1998; *Salawitch,* 1998].

Another possibility for distinguishing "chemical" and "dynamical" contributions to observed ozone trends may be associated with a simple empirical method which is based on the analysis of the data sets and high correlations between interannual variations of the total ozone and stratospheric angular momentum [*Jadin,* 1997a]. The aim of this work is to attempt to estimate at the first approximation the relative role of chemically and dynamically induced impacts on the total ozone trends. Section 2 contains data sets used and results of the analysis of the relations between interannual variations of the total ozone and stratospheric angular momentum taking into account their longitudinal asymmetry, as well as empirical estimates of the "chemical" and "dynamical" total ozone trends. Discussion of the results is presented in section 3.

2. Data and Method of Analysis

Calculations of stratospheric angular momentum were performed using the U.S. National Meteorological Center (NMC-NCEP) data on the monthly mean zonal wind at the standard levels from 100 to 0.4 hPa for January in the NH and October in the SH during 1979–1992. The TOMS (version 7) data were used for the analysis of total ozone variations. Deviations from the 1979–1992 means (anomalies) of stratospheric momentum and total ozone were calculated for each month. Stratospheric angular momentum (SAM) as the function of the longitude was calculated as follows:

$$\mathrm{SAM}(\lambda,\varphi,t) = g^{-1}a^3\cos^2\varphi \int\limits_{100\ \mathrm{hPa}}^{0.4\ \mathrm{hPa}} u(\lambda,\varphi,p,t)dp \qquad (1)$$

where a is the radius of the Earth, g is the gravity acceleration, u is the zonal wind, p is the pressure, and φ, λ are the latitude and longitude, respectively.

Stratospheric angular momentum is the useful indicator of the interannual variations both for the wave activity and stratospheric circulation and for comparison with total ozone changes. A decadal weakening (strengthening) of stratospheric wave activity may result in westerly (easterly) anomalies of the zonal wind, stratospheric angular momentum and decrease (increase) of the total ozone at middle and high latitudes during wintertime. It can be a cause of the high negative correlations between the interannual variations of the zonal mean total ozone and stratospheric momentum [*Jadin,* 1996, 1999].

In order to indicate the principal components that are mostly responsible for the interannual variability of stratospheric dynamics and ozone, first empirical orthogonal functions (EOF) (unrotated) of the total ozone and stratospheric momentum anomalies were calculated. Analysis of the relations between interannual anomalies of the total ozone and stratospheric circulation was performed using the singular value decomposition (SVD) calculations which maximize correlations between two fields of data [*Bretherton et al.*, 1992]. Several first SVD modes were calculated and used for the reconstruction of total ozone anomalies. In order to emphasize total ozone changes at middle latitudes, they were weighted on cosine of latitude.

The possibilities to reconstruct interannual total ozone variations were studied by means of the linear regression

$$\mathrm{O}_3'(\mathrm{reg}) = \frac{\mathrm{cov}(\mathrm{O}_3',\mathrm{SAM}')}{\sigma^2(\mathrm{SAM}')}\mathrm{SAM}' \qquad (2)$$

where O_3', SAM' are the observed total ozone and calculated SVD modes of stratospheric momentum anomalies, and $\mathrm{cov}(\mathrm{O}_3', \mathrm{SAM}')$ and $\sigma^2(\mathrm{SAM}')$ are their covariance and dispersion, respectively.

The real total ozone anomalies can be written as follows:

$$O'_3(\text{real}) = O'_3(\text{reg}) + \text{res} \qquad (3)$$

where res is the residual term of the regression. It can be responsible for total ozone variations which are not related to long-term changes of the stratospheric dynamics and may represent "chemical" impacts.

3. Results

There are large interhemispheric differences in the structure and interannual variations of stratospheric parameters especially during wintertime. These differences are mainly caused by differences in the propagation and intensity of the stationary planetary waves, sources of which are the orographic generation and thermal excitation associated with the sea surface temperature (SST) anomalies. Stationary planetary waves can penetrate from the troposphere to stratosphere only during seasons with westerly zonal wind in the stratosphere, i.e. during winter/spring times. The dominant disposition of continents in the NH results in differences of the wave activity and composition of the stratosphere. Analysis was conducted individually in the SH and NH for the months with largest ozone trends.

3.1. Southern Hemisphere

Figure 1 shows the first EOF (EOF1) and SVD (SVD1) modes of stratospheric momentum and total ozone anomalies expressed as correlations (%) with their expansion coefficients for October in 1979–1992. Spatial patterns of the corresponding EOF1, SVD1 and their temporal series are similar to each other, that implies their strong interannual relations. Basic features of these leading modes correspond well to the calculated linear trends of the total ozone and stratospheric momentum (not shown) and describe the long-term variability of the stratospheric circulation and total ozone, as seen from the temporal variations of the expansion coefficients. Development of the ozone hole in the Antarctic is manifested in the time series of the first EOF of the total ozone anomalies with the maximum of low-frequency changes of the total ozone in the eastern sector of the Antarctic. A negligible trend of the total ozone in the South Pacific nearly at 50°S, 120°W [*Randel and Cobb,* 1994] and the similarity of ozone variations over Argentina to the ozone hole changes [*Kadygrov and Jadin,* 1999] should be noted.

On the one hand, structures and time series of the ozone EOF1 (66.8% of the total variance) and SVD1 (64.6% of the variance of ozone) modes are almost identical. On the other hand, the SVD1 mode of total ozone anomalies is tightly associated with the corresponding EOF (30%) and SVD (23.6% of the SAM variance) modes of the stratospheric momentum anomalies. The correlation coefficients between the SVD1 ozone and SAM time series is very high (77%) and statistically significant on 95% confidence level. Strong negative minima over the South Atlantic (50°–60°S, 0°–60°W), middle latitudes of the South Pacific and central Indian Oceans are most prominent in the structures of the SVD1 and EOF1 of stratospheric momenta. Large decrease of the total ozone over eastern coast of the Antarctic is associated with the strengthening of westerly SAM anomalies especially at middle latitudes over the South Atlantic during 1979–1992. This corresponds well to the analysis of relations between the interannual zonal mean anomalies of the total ozone and stratospheric momentum [*Jadin,* 1999]. The abrupt "jump" of their coefficients in 1980 emphasizes the transition of stratospheric circulation to a new decadal regime, which has been indicated by *Jadin* [1996] for zonal mean variations of the stratospheric momentum anomalies. This transition is associated with a disappearance of abnormal features (easterly "cat eyes") in zonally-mean zonal wind anomalies centered at 50 hPa (30°S, 30°N) after summer 1980 [*Jadin*, 1997a]. The analysis showed that this transition in interannual zonal wind variations occurred mainly over the South Pacific and South Atlantic regions.

The second EOF (19.3%) and SVD (20.1%) modes of the total ozone anomalies (not shown) are also similar to each other and their structures have the dipole-like character at longitude with opposite variations between the Pacific–Atlantic and Indian Oceans at high latitudes of the Southern Hemisphere [*Kadygrov and Jadin*, 1999]. Their time series undergo sharp changes in 1981/1982 and 1991/1992. Relations between the second SVD modes of the total ozone and stratospheric momentum are weaker and their contributions to the total variance are smaller than for the first ones. Interannual variations of the total ozone and stratospheric momentum, as well as their strong interrelations can be mainly described by the first EOF and SVD modes in the Southern Hemisphere for October.

Results of the SVD analysis allow to indicate the key regions of the SAM anomalies, which are the most responsible for the interannual variations of the total ozone in the Antarctic. Westerly anomalies of the zonal stratospheric circulation dominate over the eastern South Pacific, South Atlantic and central Indian ocean after summer 1980, which led to a strong isolation of the polar vortex over the Antarctic and created favorable conditions for the ozone hole occurrence. Figure 2 illustrates relations between interannual variations of the total ozone at Halley Bay (76°S, 27°W), Syowa (69°S, 40°E), and McMerdo (78°S, 166°E) stations, the region with positive ozone trends in July (50°–55°S, 20°–40°E) [*Kadygrov and Jadin,* 1999] and stratospheric momentum anomalies (with the opposite sign) in the gridpoints with the best correlations. It is seen that the total ozone anomalies at the stations located at the coasts of the Atlantic and Indian oceans are strongly correlated with the SAM anomalies over the South Atlantic and Indian ocean. Similar relations are observed for McMerdo station, but with variations of the stratospheric dynamics outside the polar vortex over the South Pacific (65°S, 120°–130°W). Positive trends of the total ozone in July 1979–1992 nearly at 50°S, 30°E are mainly associated with the negative (easterly) trends of stratospheric momentum anomalies in the region 25°–35°S, 40°–60°E southward from Madagaskar [*Jadin,* 2001a].

Thus, there exist long-term changes of the stratospheric circulation in subtropics and middle latitudes of the South-

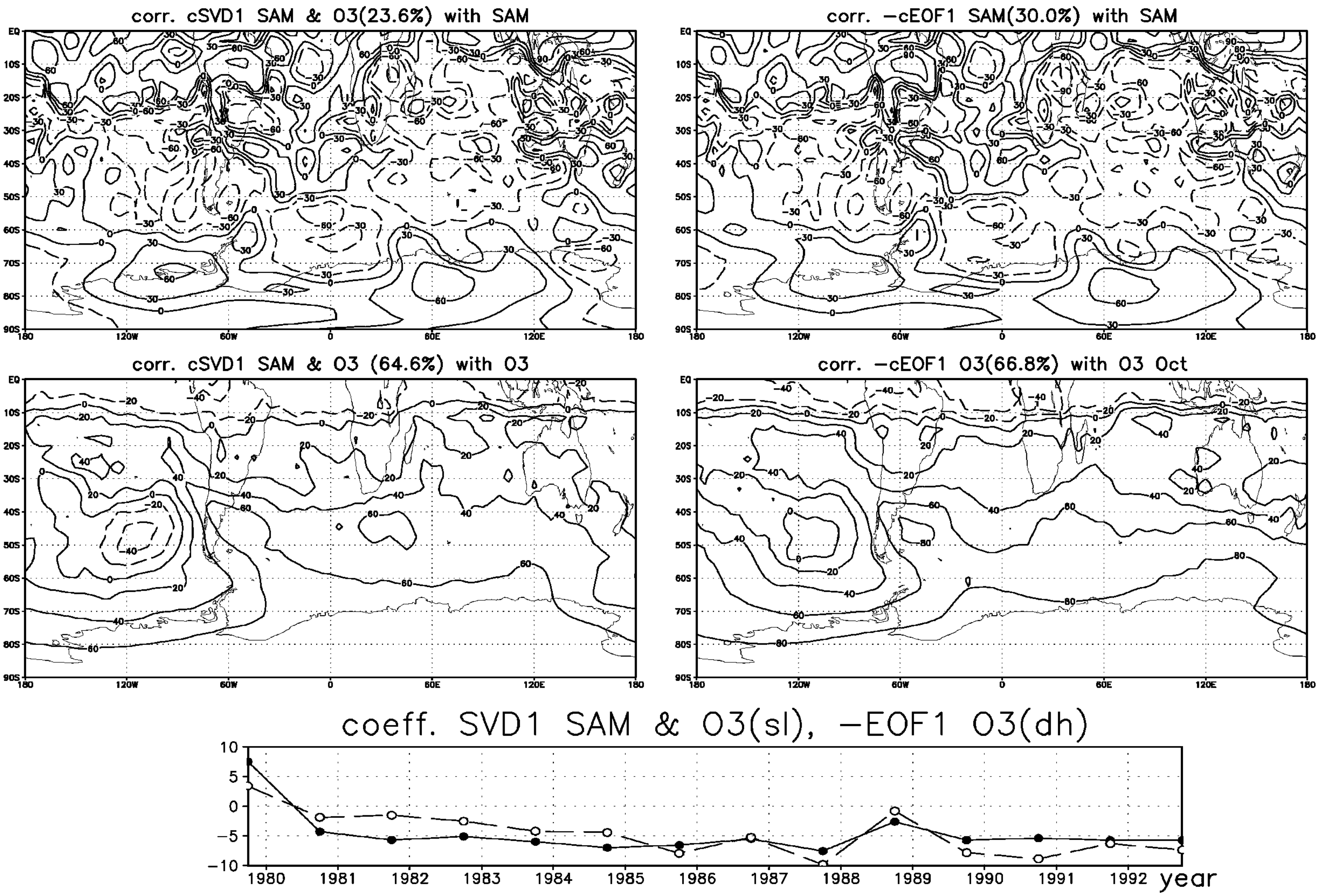

Figure 1. The first EOF and SVD modes of the stratospheric angular momentum (a) and total ozone (b) anomalies expressed as the correlations (%) of their anomalies with the temporal behavior of the expansion coefficients for October 1979–1992 (their contributions to the total variance are shown in parentheses), and (c) coefficients of the EOF1 ozone (dashed line) and SVD1 stratospheric momentum on total ozone (solid line) anomalies (in arbitrary units).

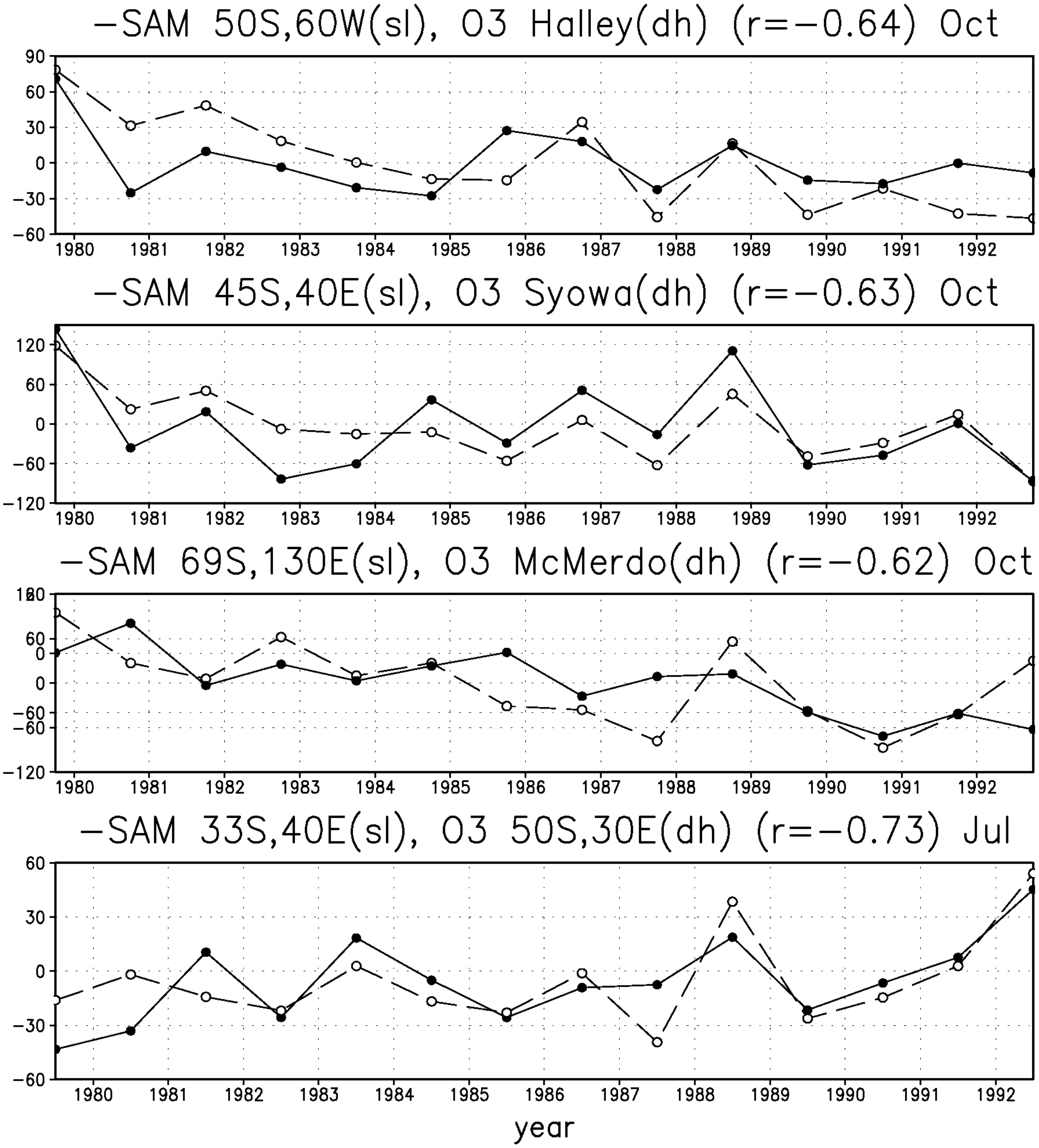

Figure 2. Total ozone anomalies (dashed lines) at Halley Bay, Syowa, and McMerdo stations for October and at 50°S, 30°E for July, and stratospheric angular momentum (with opposite sign, solid lines) in the regions with the best correlations.

ern Hemisphere in winter/spring seasons which control the degree of polar vortex isolation and interannual variations of the ozone hole in the Antarctic.

3.2. Northern Hemisphere

As it has been mentioned above, larger longitudinal asymmetry of stratospheric parameters is observed in the winter Northern Hemisphere. Therefore, it is necessary to analyze the first two EOF and SVD modes of the total ozone and stratospheric momentum anomalies at least, because they provide a comparable contributions to the total variance. Figure 3 shows the first two EOFs of the total ozone and SAM anomalies for January and their expansion coefficients. Spatial pattern of the first EOF (31.4% of variance) is in a good agreement with basic features of the total ozone trends [*Kadygrov and Jadin,* 1999; *Randel and Cobb,* 1994; *Stolarski et al.*, 1991] and describes the low-frequency variability of the total ozone, as it is seen in the behavior of its coefficient.

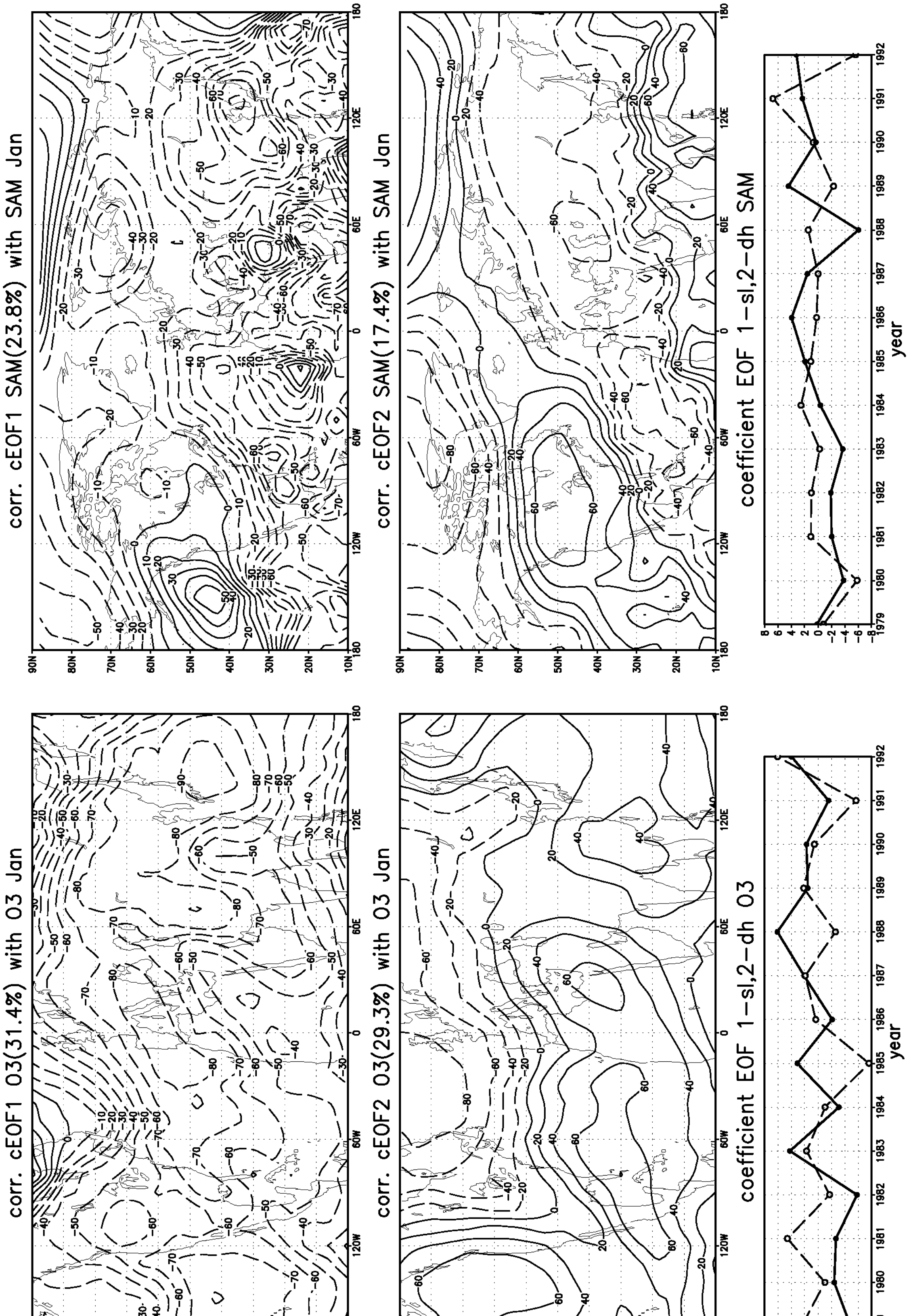

Figure 3. The first two EOFs of (left) the total ozone, (right) stratospheric angular momentum, and their coefficients (EOF1, solid; EOF2, dashed) for January. Units are arbitrary.

The ozone decrease maxima take place over Europe and European part of Russia, eastern Siberia, Far East and Japan, North Pacific, United States, and North Atlantic. Note that the total ozone increase is observed over Labrador in January 1979–1992. Spatial pattern of the second EOF (29.3%) describes opposite picture of total ozone variations between the North Pacific and North Atlantic, northern Europe, Russia with a quasi-biennial signal in its time series [*Kadygrov and Jadin,* 1999]. Analysis of the total ozone anomalies has shown that the quasi-biennial oscillation (QBO) of the total ozone has indeed opposite variations between high latitudes of the North Pacific and other regions. The total ozone variations can be explained by the constructive or destructive interference of these two modes [*Jadin,* 1999], for example, the large ozone increase over Labrador in January 1985 is mainly related to the constructive (positive) interference of the EOF1 and EOF2 contributions.

Spatial pattern of the EOF1 (23.8%) SAM anomalies are characterized by strong negative anomalies at low and middle latitudes except over the North Pacific and east Arctic. Structure of the EOF2 (17.4%) resembles that of the EOF1 with positive anomalies in the North Pacific, which are shifted towards the equator. However, the behavior of the EOF2 coefficient is different from that of the EOF1. Sharp changes are observed during 1979–1981 and 1990–1992. Again, basic features of the interannual variations of the stratospheric momentum in the NH can be explained by the constructive and destructive interference of the first EOF's contributions. It should be noted that the spatial patterns of the leading modes of the SAM anomalies resemble the well-known teleconnections of the tropospheric circulation [*Wallace and Gutzler,* 1981]. Notice also the dipole-like structure of these modes in the Arctic, that give evidences of the longitudinal asymmetry in interannual variability of stratospheric warmings.

Figure 4 shows the first two SVD modes of the relations between the total ozone and stratospheric momentum anomalies. One can see that the SVD1 (28.5% of ozone variance), SVD2 (29.8%) of the total ozone anomalies resemble their EOF2 and EOF1 respectively, as well as their time series. Spatial pattern of the SVD1 (14.1% of SAM variance) and its time series of the stratospheric momentum anomalies resemble also that of the EOF2 with some differences in the behavior of their coefficients especially during 1979–1981. The low-frequency variations of the total ozone at mid to high latitudes (EOF1 and SVD2 modes of the total ozone) are strongly associated with the SVD2 mode of the SAM anomalies which is not similar to their first two leading modes. Less clear relations between the SVD and EOF modes of the SAM anomalies as compared with those of the total ozone anomalies are not surprising. It is known [*Andrews and McIntyre,* 1976] that only the fraction of the stratospheric dynamics (namely, the residual circulation) is responsible for the transport of ozone and other species in the stratosphere. Therefore, the SVD modes of the SAM anomalies may not coincide with the leading principal patterns in contrast with those of the total ozone anomalies. It should be noted that the correlations between the corresponding SVD modes of the total ozone and SAM anomalies are very high (more than 80%) as one can see in Figure 4. This can mean that the singular value decomposition makes it possible to separate a fraction of the stratospheric dynamics, which is most strongly associated with the ozone transport. Unlike in the Southern Hemisphere, the second SVD modes of the total ozone and SAM anomalies are responsible for long-term changes of the total ozone in the Northern Hemisphere.

Relations of the total ozone anomalies over Labrador, Europe, eastern Siberia and the SAM anomalies in the points with best correlations are shown in Figure 5. These relations have a non-local character emphasizing a wave nature of the ozone transport processes. These relations hint on that the total ozone increase over Labrador during 1979–1992 is caused by an increase of the easterly SAM anomalies over the western Arctic, whereas the negative ozone trends in Europe (Siberia) are strongly linked to the increase of the westerly SAM anomalies over the north Canada (east Arctic) [*Jadin,* 2001a].

3.3. Empirical Estimates of the Total Ozone Trends

Reconstruction of interannual variations of the total ozone can be performed using calculated anomalies of the stratospheric angular momentum [*Jadin,* 1997b]. The first ten SVD modes of the SAM anomalies and total ozone anomalies "dynamically" induced were reconstructed using linear regression (2) and (3) of the real total ozone on the first ten SVD modes of the stratospheric momentum. Analysis showed that the differences between the use of the first five (or more) SVD modes and 10 modes are negligible. Figure 6 shows the results of reconstruction in the high latitudes of the NH and SH for January and October, respectively. A good qualitative agreement of the real and reconstructed anomalies is observed not only at high latitudes, but at middle and low latitudes as well (not shown). Even positive total ozone trends over Labrador are reproduced by means of this simple empirical method. Differences between the actual and reconstructed anomalies do not exceed 10–15 DU on the average. Such a good agreement is a consequence of large correlations of the total ozone variations with stratospheric dynamics, which are clearly visible in Figures 1–5.

The residual term in equation (3) can be interpreted as total ozone anomalies which are not related to interannual and interdecadal variations of the stratospheric circulation and may be caused by an anthropogenic impacts on the ozone layer. The linear trend of the residual ozone variations was calculated and its ratio to the linear trend of the real ozone variations in regions with strongest trends is shown in Figure 7. Largest trends "chemically" induced are observed over the eastern coast of United States (∼70%); France, Germany, and Italy (∼70%); Moscow region (∼60%); and Baikal, Far East, and Japan (∼50%). Strong negative trends of the observed total ozone over the North Pacific [*Kadygrov and Jadin,* 1999; *Stolarski et al.*, 1991], are mainly caused by long-term changes of the stratospheric dynamics. In the Southern Hemisphere for October, the largest "chemical" trends take place south-eastward from Australia (up to 90%) and South America (∼70%) closely to the coast of the Antarctica. There is a strong longitudinal asymmetry

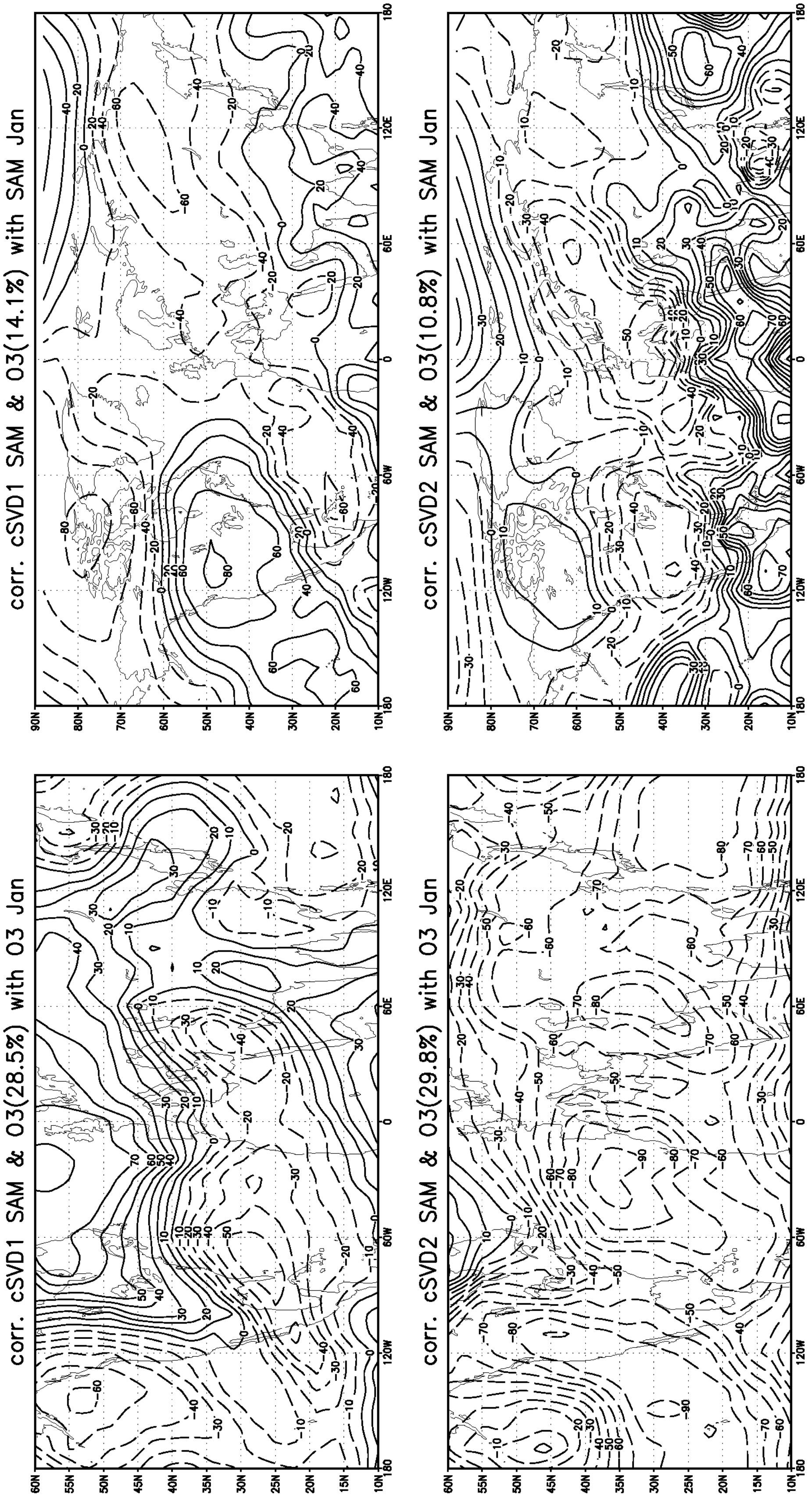

Figure 4. The same as in Figure 3, but for the first two SVD modes of (left) the total ozone and (right) stratospheric angular momentum anomalies for January.

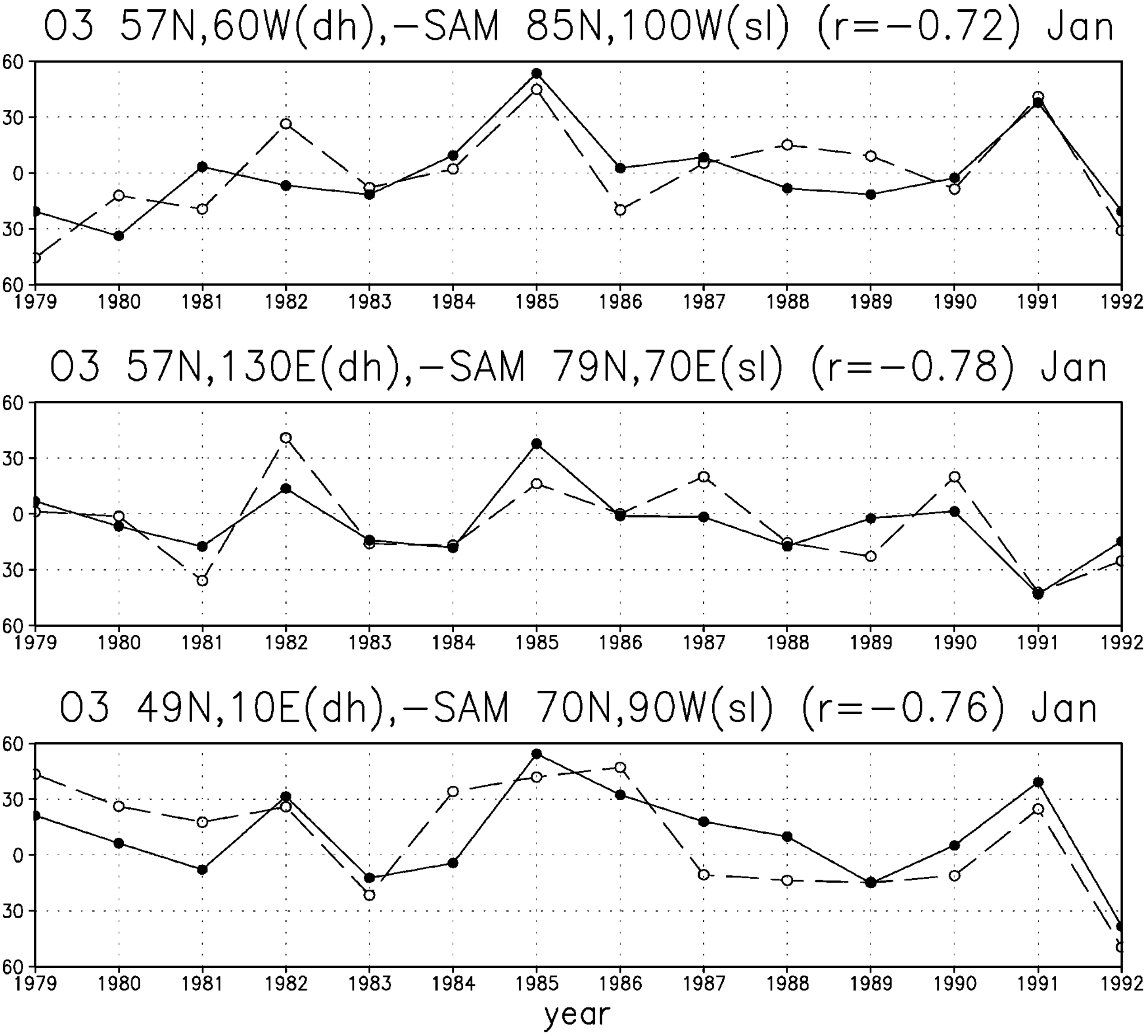

Figure 5. Relations between the total ozone (dashed lines) over Labrador, Europe, and the vicinity of Yakutsk and stratospheric momentum (solid lines) anomalies in regions with the best correlations for January.

in the calculated "chemical" trends as compared with the observed ones. Of course, these estimates should be considered as preliminary because of many feedbacks between the chemistry and dynamics of the atmosphere.

4. Discussion and Conclusions

The results presented here and by *Jadin* [1996, 1999], and *Jadin and Diansky* [1996] provide some evidences of an abrupt transition of the stratospheric circulation to a new decadal regime after the summer 1980 and its strong influence on the ozone layer. Two possible mechanisms can be responsible for these long-term changes. The first one is related to the wave hypothesis [*Jadin,* 1990]. Model simulations showed that the strongest response of the stratospheric circulation and eddy ozone transport to prescribed SST anomalies is for west-eastward shifts of SSTs (not to amplitude). This fact can be explained by an interference between the changing thermal excitation and orographic source of planetary waves. According to the wave hypothesis, subtle features of SST anomalies in the Atlantic, Pacific and Indian ocean can lead to decadal weakening of stratospheric wave activity at middle and high latitudes and the creation of favorable conditions for chemical destruction of the ozone layer. Large negative correlations between interannual variations of the total ozone and stratospheric momentum (Fig-

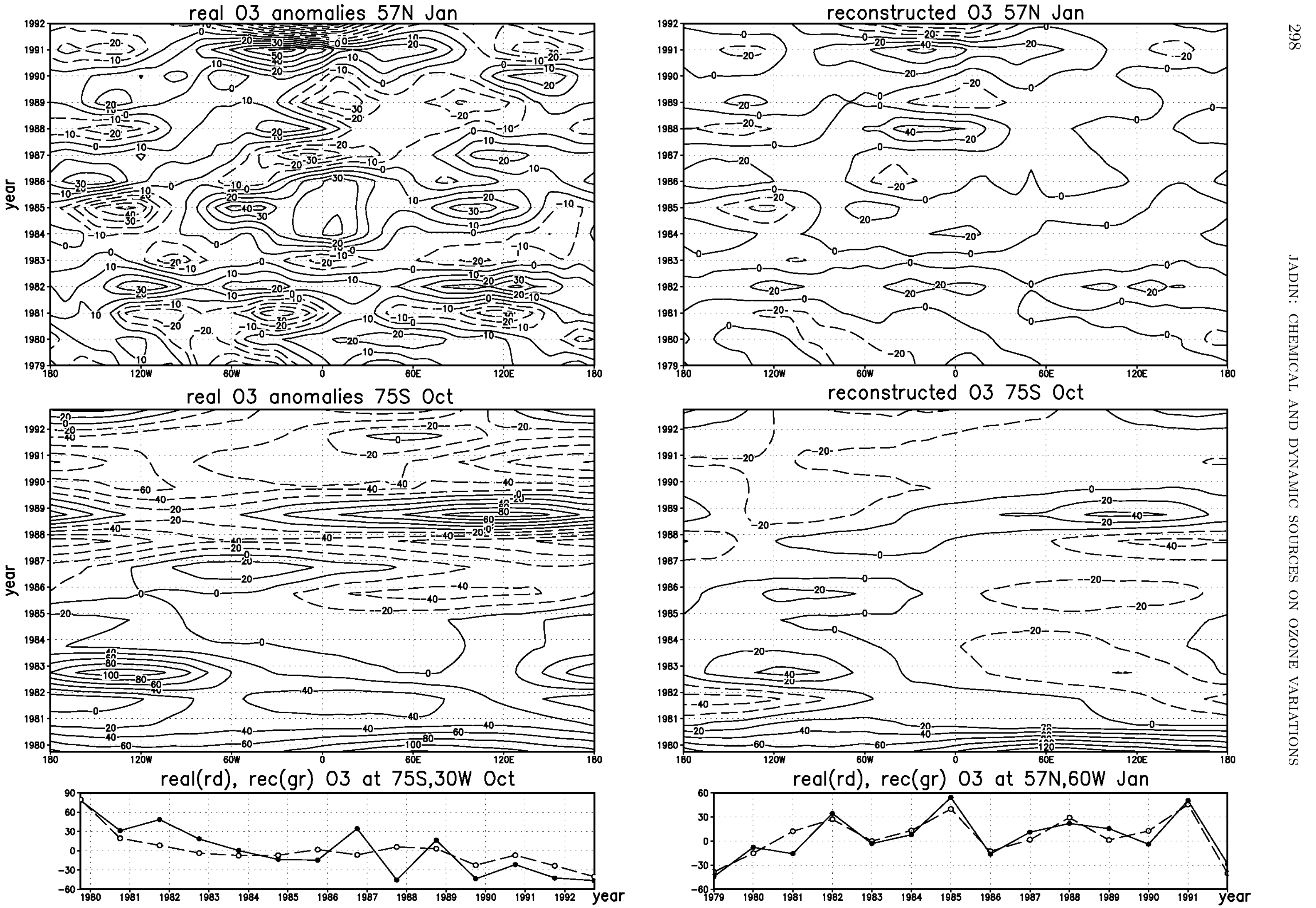

Figure 6. (a) (left) Real and (right) reconstructed total ozone anomalies (DU) at 57°N in January (top) and 75°S in October (bottom); and (b) real (solid lines) and reconstructed (dashed lines) anomalies (DU) at high latitudes of the Northern (January) and Southern (October) Hemispheres.

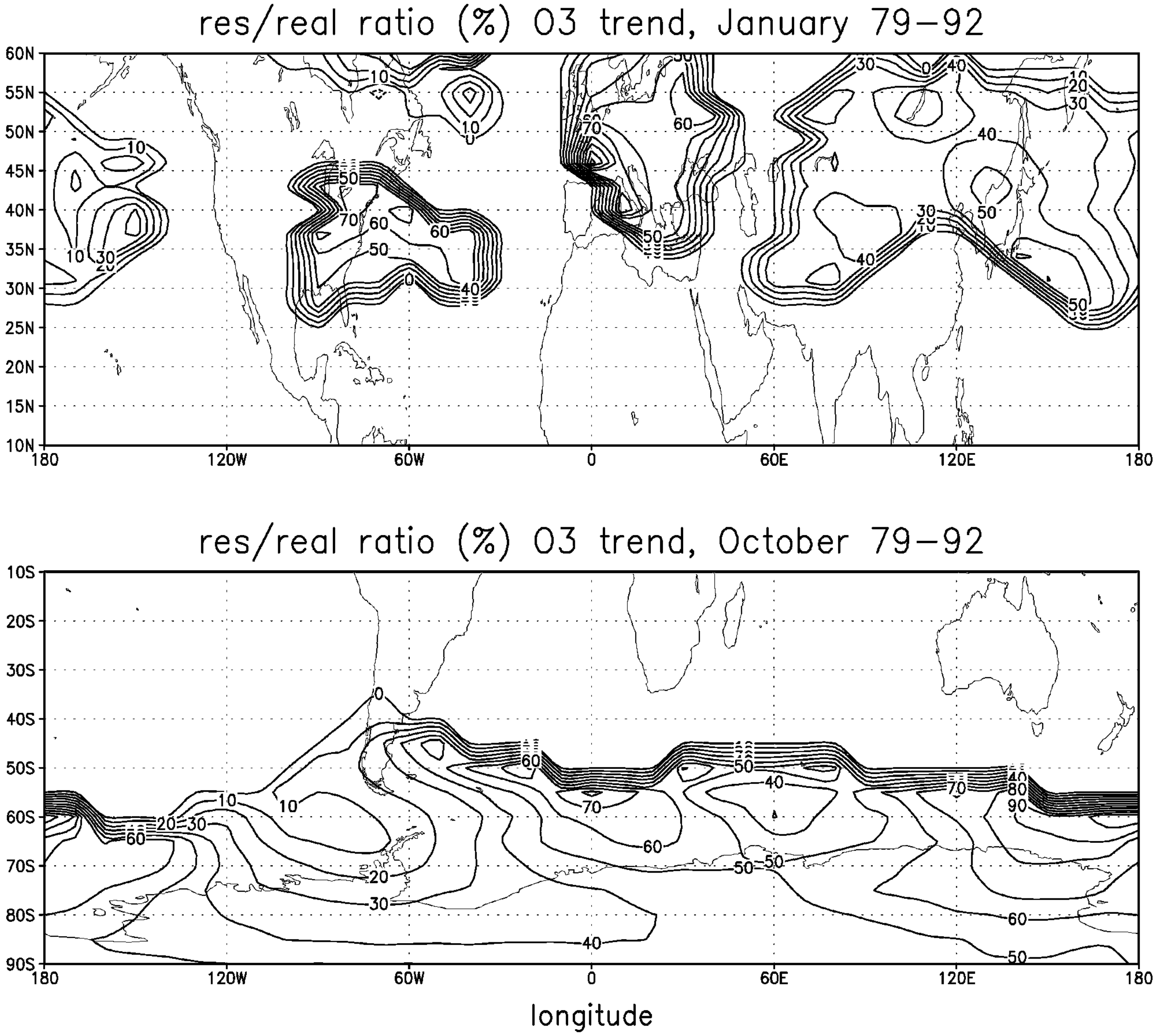

Figure 7. Ratio (%) of the "chemical" total ozone trends to those observed in (a) January and (b) October of 1979–1992 (see the text).

ures 1–5) can be explained by an interdecadal weakening of the stratospheric wave activity, because it may result in a strengthening of westerlies and decrease of the eddy ozone exchange between midlatitudes and polar regions. The second possible mechanism can be associated with the influence of radiative budget changes due to ozone decreases on the stratospheric circulation. Consequences of this mechanism are qualitatively similar to those of the first one: namely the strengthening of westerlies. Therefore, general model circulation may be used to identify the cause of large negative correlations shown in Figures 1–5.

However, there are some observational and theoretical arguments in support of the statement that the first mechanism is more preferable than the second one. *Van Loon and Tourpali* [1995] pointed out that the tropospheric circulation change in the SH in early winter from 1970s to 1980s cannot be caused by the decline in ozone during September–October. *Jadin and Diansky* [1996] showed also that the strongest strengthening of westerlies at high southern latitudes of the lower stratosphere during 1979–1992 is observed in the winter (June–August) before the ozone hole occurrence in September–November. If radiative regime changes due to the decrease of the ozone concentrations are a most important factor for interannual variations of the stratospheric circulation, then maximum of the zonal wind changes should take place during or after the ozone hole occurrence. It should be also noted that an abrupt transition of the stratospheric dynamics in the summer 1980 occurred in the subtropical lower stratosphere, where ozone changes are small as compared with those at high latitudes.

Another arguments in support of the wave hypothesis are the relations known between the interannual variations of the SST anomalies in the central equatorial Pacific and ozone hole development in the Antarctic [*Angell,* 1988; *Kodera and Yamazaki,* 1989; *Komhyr et al.,* 1991], as well as between the SST's in the North Atlantic and the total ozone over Europe during wintertime [*Jadin,* 1992]. High correlations of the total ozone variations over Europe with parameters of the Azora high pressure in winter 1958–1993 were indicated by *Bekoryukov et al.* [1994].

Recently, *Thompson and Wallace* [1998] showed that there is a strong link between the interannual and decadal variations of the extratropical tropospheric circulation and stratospheric vortex in the Arctic (Arctic Oscillation). A possible cause of the Arctic Oscillation can be the long-term changes of the SST anomalies in the North Atlantic and North Pacific (dipole "through Rocky mountains") [*Jadin,* 2001b]. It was also shown that there are very strong relations between the leading EOF and SVD modes of the interannual SST anomalies in the North Atlantic and those of the total ozone variations in the Northern Hemisphere for January 1979–1992. It is difficult to assume that the observed ozone changes could lead to significant variations of the sea surface temperature namely in the North Atlantic. For the Southern Hemisphere, there are also strong relations between the interannual variations of the ozone hole in the Antarctic, stratospheric momentum shown in Figure 1 and the SST anomalies in the South Atlantic and South Pacific (dipole "through Andes"). These results confirm the consequences of the wave hypothesis and an important role of long-term natural changes in the coupled ocean-atmosphere system in the observed trends of the ozone layer.

Empirical estimates of the relative contributions of natural and anthropogenic factors to the observed total ozone trends should be considered as preliminary because of many feedbacks between atmospheric circulation, wave activity and composition. Future simulations with the help of general circulation models which must reproduce both of long-term changes in the coupled ocean-atmosphere system and ozone layer can provide more accurate estimates.

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