Longitude-Dependent Decadal Changes of Total Ozone in Boreal Winter Months during 1979–92

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ABSTRACT

A statistical analysis shows that the decadal change of zonally asymmetric total ozone (Total Ozone Mapping Spectrometer data) has a distinct spatial similarity with the decadal change of the 300-hPa geopotential patterns during December–February of 1979–92 in the Northern Hemisphere: Regions of ozone increase correspond with regions of geopotential decrease and vice versa. An area of strong ozone decrease above Europe is surrounded by areas of ozone increase over the North America–North Atlantic region and the eastern Europe–Siberia region, in both December and January. In February the picture is changed by the appearance of a region of ozone increase above Europe. In all three months an area of ozone decrease exists in the east Asia–Pacific region, with one region in January and two regions in December and February. In all cases the centers of decadal ozone change as well as their month to month alterations are significantly anticorrelated with those of the 300-hPa geopotential.

These statistical results are investigated with a linear quasigeostrophic transport model. Taking into account 14 layers between 500 and 1 hPa the contributions of horizontal and vertical advection to ozone transport were estimated separately. In December and January the complexity of the spatial distribution of ozone change is mainly due to the contribution of advection by wavenumbers 3 and 4, but wavenumbers 1 and 2 also contribute a comparable amount. The January ozone decrease above Europe has different causes: in northeast Europe the contribution from wavenumbers 1 and 2 dominates, whereas in central Europe that from horizontal advection by wavenumbers 3 and 4 prevails. In February the spatial structure is mainly determined by wavenumbers 1 and 2 alone, with equal contributions from horizontal and vertical advection. In the vertical distribution in midlatitudes the essential contributions come from the height region between the upper troposphere and the ozone layer maximum. December’s and January’s structures are similarly determined by wavenumbers 3 and 4 with unchanged vertical phase. Here the contribution of the horizontal advection to the total decadal ozone change occurs in a higher-altitude range (100–50 hPa) and that of the horizontal together with the vertical advection in a lower-altitude range (200–100 hPa). In February the wavenumbers 1 and 2 determine to a large extent the height distribution of the ozone trend in the midlatitudes by the contribution of the horizontal advection.

1. Introduction

Long-term Northern Hemispheric ozone trends, derived from data beginning in the early 1960s (e.g., Bojkov et al. 1994), may be superimposed by decadal changes that regionally act with different intensities or even different signs. The period measured by the Total Ozone Mapping Spectrometer (TOMS) instrument on board the Nimbus-7 satellite, 1979–92, is well suited for the analysis of such a decadal change. So the decadal zonal mean total ozone change in the midlatitudes undergoes a distinct seasonal variation with highest changes during spring, about \(-7\% \text{ decade}^{-1}\), depending on the version of TOMS data used (e.g., Stolarski et al. 1991; Randel and Wu 1995; McPeters et al. 1996). The longitutude-dependent structures are most intensive in January and February (Niu et al. 1992). Peters and Entzian (1996) show that the strongest ozone change took place in January in the European region, where the deviation from the zonal mean (the zonally asymmetric decadal ozone change) reaches almost the same amount as the zonal mean decadal ozone change itself, that is, about \(-7\% \text{ decade}^{-1}\). With it the decadal total ozone change above central and northern Europe in January is about twice that of the zonal mean. Peters and Entzian (1996) further show that there exists a significant statistical connection between longitude-dependent decadal ozone change and that of 300-hPa geopotential height in their spatial structures. The geopotential of 300 hPa was chosen as an indicator of middle-troposphere to lower-stratosphere dynamics. In order to study the longitude dependence it is usual to work with the deviations from the zonal mean. To get the zonally asymmetric dependence of the geopotential or of ozone for different months we subtracted the respective zonal mean from the monthly average at each grid point.

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As was shown by Hood and Zaff (1995) and Peters et al. (1996, hereafter PES), it is possible to describe the longitude-dependent decadal ozone change of January 1979–92 relatively well with a linear transport model, where any decadal alteration in the geopotential field tends to yield a corresponding observed total ozone change. They ran model calculations for two distinct averaged year groups and estimated an approximation of decadal total ozone change through their difference. To do so was only possible because (i) the model gives a good representation of the January climatic state over 14 yr and (ii) the difference between some mean year groups at the beginning and at the end of the TOMS period explains the spatial structure of the linear regression with time very well. Furthermore PES have discussed the different contributions of horizontal and vertical advection as a function of ultralong waves with wavenumbers 1–2 and 3–4 and pointed out that the contribution of horizontal advection by wavenumbers 3 and 4 dominates the observed total ozone change over central Europe. The separation of waves into two classes of two wavenumbers each, which proved useful (PES), will be continued in this paper.

The aim of this paper is to examine whether a significant longitude-dependent decadal ozone change exists in connection with geopotential alterations in winter and if there is a significant variation of the zonally asymmetric decadal ozone change from month to month. Maps of monthly averaged longitude-dependent decadal ozone changes were created by linear regression of these zonally asymmetric values with time. First we will look at the statistical significance of these decadal ozone changes themselves at each grid point and that of their spatial structures, then at the significance of their regression with geopotential height changes, and finally at that of the pattern differences from month to month. Following this, we will compare the total, horizontal, and vertical advection contributions of ultralong waves to the longitude-dependent decadal ozone changes for each winter month in the period 1979–92 of the Northern Hemisphere by using a linear transport model.

In section 2 the datasets and methods of investigation are described. In section 3 the results are presented for the statistical analysis and for the model calculations. The discussion and conclusions are given in section 4.

2. Datasets and methods of investigation

a. Datasets

Total ozone values were taken from TOMS in the period 1979–92 [version 6; McPeters et al. (1993)], in the form of monthly mean values December, January, and February. For statistical analyses a gridpoint resolution of 5° lat × 10° long was used. The deviation from the zonal mean was calculated in each grid point between 20° and 60°N, because data north of about 60°N are not permanently resolved by the TOMS equipment in winter. For model calculations the amplitudes and phases of the geopotential as well as the zonal mean fields of temperature and zonal wind were taken from the climatology of the National Centers for Environmental Prediction (Randel 1992). The temperature field was determined by the hydrostatic relation. The zonal mean ozone distribution of the Northern Hemisphere, necessary for the model, was taken from McPeters et al. (1984).

b. Observational analysis

For the statistical analysis at each grid point the linear regression with time was calculated for total ozone deviation from the zonal mean and for that of the 300-hPa geopotential height. The resulting spatial structures, their similarities between both parameters, and their change from one month to another were analyzed for statistical significance. Here simple statistical methods of correlation and regression coefficients (Taubenheim 1969) are sufficient rather than sophisticated ones, like singular value decomposition or canonical correlation analysis. To test if the spatial structures themselves are significant, the trend of total ozone deviation from the zonal mean and the trend of geopotential height deviation, respectively, were tested for significance at each grid point (described in detail by Peters and Entzian 1996). The similarity of the respective spatial structures was tested with the spatial correlation coefficient, found from the scatter diagram of the trend values taken from every grid point: The resulting regression coefficient in (DU yr⁻¹)/(gpm yr⁻¹) (equivalent to DU gpm⁻¹; DU: Dobson unit) gives the ozone change relative to the geopotential change. The alteration of the total ozone trend from month to month was further analyzed by checking the trend difference of the respective two months also in each grid point. All mentioned correlation or regression coefficients were tested by Fisher’s f test.

c. Linear transport model

The employed model is based on the well-known linearized stationary transport equation (e.g., PES after Kurzejma 1984), where \( \eta^* \) is the mass mixing ratio of a longitude-dependent tracer. It reads

\[
\frac{\nabla}{a \cos \varphi} \frac{\partial \eta^*}{\partial \lambda} = -\frac{v^* \partial \eta^*}{a \partial \varphi} - w^* \frac{\partial \eta^*}{\partial Z},
\]

with

\[
Z = -H \ln \left( \frac{P}{P_s} \right),
\]

where \( Z \) is the vertical coordinate, \( \lambda \) the longitude, and \( \varphi \) the latitude. Here, \( P \) represents the pressure and \( P_s = 1000 \) hPa; \( a \) is the earth radius and \( H \) the scale height. In addition, \( (U, v, w) \) represents the velocity compo-
3. Results

a. Diagnostics

In Fig. 1 the longitude-dependent decadal ozone changes are shown in the period 1979–92 for the three winter months. Positive and negative linear regression coefficients with time show distinct spatial patterns. In their centers these decadal ozone changes are significant. The longitude structures are similar to Niu et al. (1992), but here without the inclusion of the zonal mean trend.

These patterns remain quite similar during December and January above the North America–North Atlantic–European region. A region of strong ozone decrease above central Europe is surrounded by an area of ozone increase expanding from North America to western Europe and east of central Europe.

In January the December center of ozone decrease is shifted southeastward with an intensification and concentration of the pattern. Also the North America pattern of positive ozone trend is shifted eastward with an increase and maximum values over the North Atlantic. In February the former region of negative ozone change over central Europe is replaced by the region of positive ozone change over the North Atlantic, which has shifted even further eastward. Between this and a second band of positive trend over southwest Asia only a small region with a weak ozone decrease remains. From the two areas of negative ozone change over east Asia and the central Pacific in December, the east Asian region intensifies strongly in January. In February the pattern is again separated into two areas with centers at 150°W and 120°E.

In PES an interpretation was given that the west Atlantic pattern of the geopotential height trend had intensified above the North Atlantic–European region in the 1980s. As shown in Fig. 2b, this intensification takes the form of a wave track from the North Atlantic across Europe up to the Urals. This wave track can also be found in December over the North Atlantic–European region (Fig. 2a). In December another wave track occurs above the North Pacific with a distinctly southern direction. In February (Fig. 2c) a wave track exists over North America from Alaska, Labrador, to western North Atlantic.

To get an objective measure for the connection of both parameters, the spatial correlation of decadal change values of ozone (Fig. 1) and geopotential height (Fig. 2) was analyzed. This correlation of the 252 grid points used results in a scatter diagram from which the
parameters could be found, as given in Table 1. In all three months ozone and geopotential decadal change are significantly anticorrelated with correlation coefficients between $-0.58$ and $-0.74$. Before carrying out the significance test it had to be proved whether there is an autocorrelation in the spatial distribution of the gridpoint data and how many of the original 252 grid points are effectively independent (Taubenheim 1969). In the worst case (January) there remain 39 effectively independent grid points. Even so, the given correlation coefficients are significant at better than 99%. The regression coefficients between ozone and geopotential trend are between $-0.10$ and $-0.17$ DU/gpm.

The important question remains whether the variations of the decadal change from month to month are also significant. In Fig. 3 these variations are given as differences. For example, the intensifying and eastward shift of the North America–North Atlantic region of positive decadal ozone change from December to January, as well as the replacement of the area of ozone decrease by an area of ozone increase above central Europe from January to February, prove to be significant. The spatial structures of the decadal changes of the geopotential heights undergo very similar changes.

Where the January ozone decrease changed to an increase in February (e.g., Fig. 3b; over Europe) the geopotential trend decreases significantly (see Fig. 3d). A spatial correlation of these alterations of the decadal change of ozone and geopotential height shows significant correlation coefficients, also given in Table 1. They vary between $-0.59$ and $-0.78$. Here the number of effectively independent grid points is 34 at its smallest, which, nevertheless, gives a significance of more than 99%. The regression coefficients are between $-0.12$ and $-0.17$ DU gpm$^{-1}$, which is again in the above-mentioned order.

b. Model calculations

The statistical results given so far on the connection between ozone and geopotential trends are remarkable and they give rise to the assumption that the alterations found in the dynamics may be the reason for the zonally asymmetric ozone change, but whether there is indeed a physical interaction cannot be determined. Therefore we investigated the data with the help of the above-mentioned linear quasi-stationary model equation (1). To describe the trend we calculated two 5-yr means; one at the beginning of the aforementioned period 1979–92, that is, 1979–83, and one at the end of the period, that is, 1988–92. The difference between the periods should represent the trend (Fig. 1). Figure 4 shows how well this difference replaces the trend and will be used for further comparisons with model results. The differences for each month show a good agreement with the linear regression fields in Fig. 1. So the aforementioned model strategy to calculate first the stationary solution for each 5-yr group and then to form the model difference from them is supported in each month. In Fig. 5 the model differences are given for December, January, and February. If we compare the differences in Fig. 4

![Figure 2. Trend of geopotential height (300 hPa) given in dam (10 yr)$^{-1}$: (a) December, (b) January, and (c) February 1979–92. White lines indicate areas of significant (>95%) trends.](image)

Table 1. Results of spatial correlation of decadal change of ozone and geopotential height and its differences; $r$ = correlation coefficient, $b$ = regression coefficient (DU gpm$^{-1}$); number of used grid points, 252; effectively independent grid points (worst case), 34; significance in all cases, >99%.

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<td>−0.70</td>
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<td>$b$ (trend)</td>
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<td>−0.12</td>
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<td>$r$ (trend differences)</td>
<td>−0.59</td>
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<td>$b$ (trend differences)</td>
<td>−0.14</td>
<td>−0.12</td>
<td>−0.17</td>
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Fig. 3. (a), (b), (c) TOMS data difference of decadal change from month to month for ozone deviation from zonal mean and (d) geopotential height deviation from zonal mean: (a) Jan – Dec; (b), (d) Feb – Jan; (c) Feb – Dec. Hatched areas are more negative than −5 DU (10 yr)^−1 or −5 dam (10 yr)^−1, respectively. Thick lines indicate areas of significant (>95%) change from month to month.

Fig. 4. Stereographic projection of differences, (1988–92) minus (1979–83), of total ozone (TOMS) for boreal winter months, in DU. Areas more negative than −5 DU are hatched.

and Fig. 5, the large-scale structure shows a good agreement for each month. Especially over the North Atlantic–European region, the decrease in December, centered over the North Sea, is resolved as well as its eastward shift, intensification, and concentration in January, which is bordered by positive trend patterns on the east and west flanks in both months. The eastward shift of this westerly positive area continuing until February is also realized by the model. So in February an ozone increase is found over the northeast Atlantic–western European region, which is opposite to the differences in December there; the ozone decrease over central Eu-
rope in January vanishes in February. Note that in Fig. 1 this was also found in the linear regression fields of the observed data. Over the east Pacific the maximum decrease in January is not well captured by the model, but the splitting into two different minima at 120°E and 140°W in February is represented surprisingly well.

In Fig. 6 the contribution of waves 1–2, and in Fig. 7 that of waves 3–4, to the total ozone difference are presented. For the contribution of waves 1–2 over the North Atlantic–European region we found an ozone decrease in December but a strong increase in February. In January the decrease is centered over northeast Europe. In December the negative contribution of waves 3–4 over Europe is as large as that of waves 1–2 and is bordered by positive trend patterns. It shows an eastward shift, intensification, and concentration in January, and is relatively unimportant in February. So the eastward shift of ozone decrease, intensification, and concentration, and its vanishing in February, is caused by the different stationary wave transport changes of both wave classes in the North Atlantic–European region.

The eastward shift and intensification of the positive trend pattern can be described analogously.

To go further into the different transport dynamics, selected contributions of horizontal and vertical transport terms on the right-hand side of Eq. (1) for both wave classes are given in Fig. 8. The contribution of horizontal advection by waves 1–2, Fig. 8a, is in phase with that of waves 3–4, Fig. 8d, and also with that of vertical advection of waves 3–4 above Europe (for this compare Fig. 8d and 7a). It follows that the total ozone decrease over the North Atlantic–European region in December is as large and intense as observed (Fig. 4a). In January the decrease over central Europe is mainly determined by the contribution of horizontal advection for waves 1–4, Fig. 8b, because the vertical contribution for waves 1–4, Fig. 8e, is near zero there. On the other hand the decrease over northern Europe is dominated by wave 1–2 transport changes, Fig. 6b; see also PES.

In February the increase in the North Atlantic–European region is caused by nearly equal contributions of hor-

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![Fig. 5. As in Fig. 4 but for model results, contribution of waves 1–4.](image-url)

![Fig. 6. As in Fig. 4 but for model results, contribution of waves 1–2.](image-url)
FIG. 7. As in Fig. 4 but for model results, contribution of waves 3–4.

FIG. 8. Stereographic projection of differences of total ozone, model results in DU; (a)–(d) contribution of horizontal advection; (a) for waves 1–2 in December and (c) in February but for waves 3–4 in (b) January and in (d) December, (e) the January contribution of vertical advection of waves 1–4 and (f) the February one of waves 1–2.
Fig. 9. Longitude–height sections at 50°N of ozone change in DU (yr km)\(^{-1}\). Model results, contributions of waves 1–4: (a) December, (b) January, (c) February. Differences between isolines 0.02 DU (yr km)\(^{-1}\), dashed lines indicate areas of negative trend; zero lines omitted.

The model enables one to calculate vertical profiles of the longitude-dependent ozone trends. Some January results typical for central and northern Europe are already discussed in PES. Here we want to compare longitude–height cross sections of planetary-wave-induced ozone changes for mean latitudes (we chose 50°N) for the three winter months. In Fig. 9 the model results are shown. The patterns are dominated by vertical multifold layered wavelike structures of equal phase from the upper troposphere up to the lower stratosphere. December and January (Figs. 9a and 9b) show some similarities: In both months there are strongest trend values in the sector between the North Atlantic and Siberia and a predominance of two layers, one between 200 and 100 hPa, the other between 100 and 50 hPa. The approach of the North Atlantic–European centers to the western Siberian one from December to January, as seen in Figs. 5a and 5b for total ozone, can now be seen to take place with nearly constant vertical phase in the aforementioned height region. This structure is mainly caused by the contribution of the advection of waves 3–4 (not shown), where in both months the horizontal advection contributes mainly to the ozone change in the upper level while the horizontal and vertical advectons contribute equally in the lower level.

In February the ozone change distribution has a less complex structure. It is dominated by the advection of waves 1–2 (cf. Figs. 9c and 10a), characterized by one large area of ozone increase from North America to Siberia and one area of ozone decrease split into two centers over east Asia and the North Pacific. With respect to the vertical distribution these centers are situated mainly between 200 and 100 hPa. From Figs. 10b and 10c it can be seen that the relatively simple structure results from the superposition of the more complexly structured contributions of the horizontal and vertical advection. Again the two layers 200–100 and 100–50 hPa prevail, but in contrast to December and January the vertical advection now provides the stronger contribution in the upper level and the horizontal advection mainly in the lower level. The contribution of the horizontal advection also shows two areas of ozone change in the region between 100 and 50 hPa, which are compensated finally by the two regions of the vertical advection. Of the analyzed months noticeable contributions above 20 hPa exist only in February, that is, above the ozone layer maximum. An inspection of Fig. 10b shows that this is primarily a contribution of horizontal advection of waves 1–2.

4. Discussion and conclusions

The statistical analysis shows that the longitude-dependent total ozone and the 300-hPa geopotential underwent significant decadal changes during winter months in the Northern Hemisphere between 1979 and 1992. These ozone changes are significantly anticorrelated with those of the geopotential height changes at 300 hPa. Both show similar, significant anticorrelated spatial structures. The alteration of these decadal changes from month to month also shows significant spatial structures in the total ozone and 300-hPa geopotential trends, which are again significantly anticorrelated. As mentioned above the 300-hPa level was chosen as an indicator of middle- and upper-troposphere and lower-stratosphere dynamics. Tests showed that similar results were obtained with the geopotentials in the region between about 500 and 200 hPa. This strongly suggests that decadal changes of dynamics in the above-mentioned region have an essential influence on the illustrated longitude-dependent decadal changes of the total
Fig. 10. Longitude–height sections at 50°N of ozone change in DU (yr km)^{-1}. Model results, February, contributions of waves 1–2; (a) sum of horizontal and vertical advection, (b) horizontal advection, (c) vertical advection. Differences between isolines 0.02 DU (yr km)^{-1}, dashed lines indicate areas of negative trend; zero lines omitted.

ozone during winter in the Northern Hemisphere. That dynamical parameters of the lower stratosphere, at say 100 hPa, also show a good correlation with total ozone has been used by Hood et al. (1997) for an empirical model. This can be understood due to dynamical coupling from the upper troposphere to the lower stratosphere by ultralong waves excited in the lower troposphere.

The influence of geopotential changes between the middle troposphere and lower stratosphere on ozone changes was investigated in more detail with a linear quasigeostrophic transport model. With a time-independent zonal mean ozone distribution, and without chemical source terms, it was possible to describe to a high degree the large-scale structures of longitude dependence of the total ozone trend of each winter month, especially in the North Atlantic–European region. The alteration from month to month in its longitudinal structure was also quite well resolved by taking into account the quasi-stationary waves 1–4.

Influences of ozone chemistry on the zonally symmetric ozone trend have been described by different authors, for example, Solomon et al. (1996) or Callis et al. (1997). We estimated this effect on the results of the zonally asymmetric ozone trend and found that an inclusion of a time-dependent zonal mean ozone field (not shown) influences our results unimportantly by less than 10%. So it follows that the decadal variations of the dynamical processes are responsible to a large extent for the large-scale structure of longitude-dependent total ozone trends in the boreal winter months of 1979–92.

The trend structure above Siberia and the northern Pacific is well described by the transport model during December and February, whereas in January it is underestimated by 50%; that is, during January processes are effective that are not taken into account by the linear transport model. Transient wave transports and ozone fluxes determined as a projection of the contribution of quasi-stationary waves on longitude [e.g., (v^* \eta^* )^*], not taken into account in our model, may have also an influence on the zonally asymmetric ozone change. Further, an additional chemical influence of longitude-dependent sources and sinks is not considered. Investigations will be carried out in the future as to which of these processes might describe the January deficit.

Note that the zonal mean ozone trend is to a less extent also influenced by transport processes (e.g., Callis et al. 1997) whereas the global net loss of ozone results from an enhancement of ozone destruction in the atmosphere, but these are not subjects of this investigation.

Nevertheless, the complexity of the zonally asymmetric trend structure during December and January is chiefly determined by advection of waves 3–4, while the waves 1–2 contribute a comparable amount, too. The main structures are centered in the North Atlantic–Europe–Siberia sector especially in January. Differing contributions give rise to various ozone decreases above Europe: in northeast Europe the contribution of horizontal advection of waves 3–4. In February the spatial structure of total ozone is determined by waves 1–2 alone, with nearly equal contributions from horizontal and vertical advection.

The contribution of the horizontal and vertical advections to the decadal total ozone change in winter months was estimated by the calculation of its vertical distribution in 14 height levels for mean latitudes. The main contributions come from the height region between the upper troposphere and the ozone layer maximum, with two main layers, one between 200 and 100 hPa,
the other between 100 and 50 hPa. Contributions above the ozone layer maximum can only be recognized in February resulting from contributions of the horizontal advection of waves 1–2.

Interesting results are the height-independent locations of the horizontal ozone trend extrema in December and January and their concentration at two distinct heights. This is due to the dominance of waves 3–4 in the North Atlantic–European region in mean latitudes because, unlike wavenumbers 1 and 2, these waves have no strong phase inclinations with height as revealed by an extra analysis (not shown). The two extrema can be assigned to horizontal advection in the upper layer and to equal contributions of horizontal and vertical advections in the lower layer. A completely different situation exists in February (Fig. 10). Almost all contributions to the trend come from waves 1–2. Since part of the horizontal advection contribution compensates that of the vertical advection, the contribution of the horizontal advection of waves 1–2 is left with a relatively simple vertical structure between 200 and 50 hPa. From the theory of Charney and Drazin (1961) we would expect that a decadal change of the conditions for vertical propagation of ultralong waves could contribute to the ozone trend around the 15-hPa level. The dominance of the horizontal contribution is obviously related to a relatively weak vertical velocity $w^*$ in the mean stratosphere in the midlatitudes. Hence, between January and February the dynamics have changed in such a way that the wave 3–4 activity has decreased in the North Atlantic–European region and that of waves 1–2 has increased.

It remains unexplained why the dynamic field has undergone the observed decadal change in the Northern Hemisphere in winter. These decadal changes during the 1980s are currently being investigated by numerous authors, to determine whether the decadal changes are part of the natural variability or not. The large-scale structure in the North Atlantic–European region in January (Fig. 2b) has already been compared by PES with the west Atlantic pattern as shown by Wallace and Gutzler (1981). The wave track is oriented from southwest to northeast. A further study of the 500-hPa geopotential deviation is presented for January in Fig. 11b. In the North Atlantic–European region it shows a distinct North Atlantic pattern (NA) in the period 1979–88, which also reflects the aforementioned wave track. In Fig. 11a the result is given for the 1970s, where, however, an opposite NA pattern occurs. It reveals a strong decrease in the geopotential heights, especially over Europe, from 1969 to 1979 which is in significant (significance level >95%) contrast to the strong increase in the 1980s. This may indicate that the results are connected to the interdecadal variability of the NA oscillation. Due to the correlation results in Table 1 we can extrapolate that a decadal increase of total ozone deviation should have been observed above Europe in the 1970s. A very similar wave track exists in the same region in December (Fig. 2a), but it does not appear in the 1970s. The geopotential change structure in February (Fig. 2c) is clearly different. A wave track exists over North America that is built up only from waves 1–2, but with a remarkable phase jump over the western North Atlantic at a latitude of about 45°N. As already shown by Hoskins and Karoly (1981) the wave tracks are dependent on the barotropic basic state. The vertical propagation of ultralong waves is a function of the vertical distribution of zonal mean wind, for example, Charney and Drazin (1961). Therefore decadal changes in the basic stream can have an essential influence on planetary wave propagation and the position of their wave tracks. The excitation processes of these quasi-stationary waves are located in the lower troposphere, being especially dependent on decadal changes in sea surface temperature or transient eddy fluxes. The changed forcing of Rossby waves and their internal propagation processes are investigated with the help of GCM experiments; for instance in dependence on climatological variations of the sea surface temperature; for example, Lau (1985). The large-scale patterns, found by numerous authors in different GCM runs, show great variability, which does not allow for a clear link to the observed patterns up to now. Further investigation is necessary here.
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REFERENCES
—, and Coauthors, 1993: Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) data products user’s guide. NASA Ref. Publ. 1323, 89 pp. [Available from NASA/Center for Aerospace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090-2934.]