NOTES AND CORRESPONDENCE

The Seasonal Cycle of Longitude-dependent Ozone Transport by Large-scale Waves in the Northern Hemisphere

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Abstract

The dependence of longitude-dependent total ozone patterns on large-scale wave structures is analyzed by a pattern correlation of the mean fields (climatology), as well as of the decadal change (trend) for the 1979 to 1992 period. In all months, there exists a significant negative regression between total ozone and 300 hPa geopotential height patterns for the climatology (annual average: -0.18 DU/m), and for the trend (-0.14 (DU/10 years)/(m/10 years)). For both, the regression coefficients exhibit an asymmetric annual variation with respect to the solstices with significantly higher values in spring, and lower values in autumn. Assuming that the ozone transport is primarily caused by the annual variation of large-scale wave transport in a background ozone field, we show that the seasonal cycles are mainly determined by the asymmetric annual variation of the gradients of the zonal mean ozone field, and not by the annual variability of the wave activity.

1. Introduction

In winter the longitude-dependent distribution of extratropical ozone in the northern hemisphere is essentially determined by transport processes, as known from many studies. Dobson et al. (1929) already showed a connection between meteorological fields and ozone over the European region, i.e., that low (high) pressure systems are connected with higher (lower) values of total ozone. Since then, these transport processes have been repeatedly analyzed statistically, or by models for different regions and for different space and time scales, e.g., Hartmann and Garcia (1979), Kawahira (1982), Watanabe et al. (2002). Kurzeja (1984)

showed that during winter the longitude-dependent total ozone distribution of the northern hemisphere is mainly caused by large-scale wave transport in the upper troposphere and lower stratosphere (in short UTLS). Note, these large-scale waves are defined as the very first harmonic components of the deviation of a monthly averaged quantity, from its zonal mean value.

By investigating the longitude-dependent ozone trend-like changes Hood and Zaff (1995), and Peters et al. (1996) also found the important role of large-scale wave transport of ozone in determining the ozone change for January of the period 1979–1992. Further, for climatological and decadal change, they showed the existence of significantly anticorrelated patterns in monthly averaged maps of geopotential in the UTLS region and of total ozone; in particular, McCormack and Hood (1997) investigated January and February months; Peters and Entzian (1996, 1999) examined December, January,

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February; and Entzian and Peters (1999) investigated March. This similarity between geopotential and total ozone patterns occurred, as mentioned before, due to ozone transport changes by quasi-stationary planetary waves.

In winter, in a zonal basic stream, tropospheric forced planetary waves propagate westward and upward into the stratosphere. The induced longitude-dependent wind fields transport ozone horizontally and vertically, which is irreversibly mixed by small-scale processes. Important for the net advection of ozone are not only the wind components, but also the strength of the horizontal and vertical gradients of zonal mean ozone. As known from many studies, these zonal mean ozone gradients have the strongest effects on the longitude-dependent ozone advection, from the middle troposphere up to the ozone layer maximum at about 70 hPa. However, the decadal change of the wind components are primarily responsible for the structure of longitude-dependent decadal ozone change, due to advection in winter months of the 1980s (Peters and Entzian 1999).

The understanding of the annual variation of the dynamically induced longitude-dependent ozone distribution for climatology and trend is important, e.g., for assessing chemical ozone depletion at any location. Note, that the longitude-dependent ozone trend can contribute considerably to the local ozone decreases besides the zonal mean ozone trend. For January, Peters and Entzian (1996) showed that over Central Europe both trend components were of the same order during the 1980s, i.e., that over Central Europe the total ozone decrease was twice that of the zonal mean trend.

The annual variation of zonal mean ozone is the result of the annual variation of the residual circulation, and that of the divergence of zonal mean ozone-eddy fluxes in combination with chemical ozone loss, and production in different latitudes and altitudes. Reviews of the zonal mean transport circulation, and chemistry of ozone, are given in the book of Andrews et al. (1987) or in other reports (e.g., Holton et al. 1995; Solomon 1999), and are beyond the scope of this paper.

The annual variation of the connection between the longitude-dependent upper tropospheric geopotential height, and that of total ozone was statistically analyzed by Petzoldt

(1999). For the latitude of 60°N, she found a high anticorrelation between both fields for the whole year. After eliminating the influence of different parameters (solar cycle, quasi-biennial oscillation, El Niño-Southern Oscillation), the deseasonalized link between the temperature perturbation and total ozone perturbation, was analyzed by Randel and Cobb (1994). They found a high correlation between both fields in the extratropics of both hemispheres.

However, the annual variation of large-scale wave transport of ozone, and its influence on the longitude-dependent ozone, were not the focus of these studies. Therefore, in this paper we investigate the annual variation of the influence of large-scale waves on the longitude-dependent ozone distribution, in midlatitudes of the northern hemisphere, for the climatology as well as for the decadal change. A statistical approach, the well-known pattern correlation (e.g., v. Storch and Navarra 1995) is used. It permits one to estimate the linear relation between the patterns of different distributions, and its significance. In section 2 data and the method used are described, the results are given in section 3 and are discussed in section 4.

2. Data and method

Total ozone from Nimbus 7 TOMS satellite measurements (version 7, 1979–1992, McPeters and Beach 1996) and geopotential height at 300 hPa from the NCEP reanalysis data set (Kalnay et al. 1996) have been used. The originally denser data were reduced in both data sets to a grid-point latitude $\times$ longitude resolution of $5^\circ \times 10^\circ$. The 300 hPa layer was chosen, because at this layer the geopotential is a good indicator of UTLS planetary waves (an analysis (not shown) between 500 and 70 hPa confirmed this). Monthly mean values of both data sets were calculated at each grid point and their deviations from zonal means (called perturbation for short, indicated by * at symbols in Figures). From the perturbation data sets we calculated at every grid point two basic values: the average over 14 years (called climatology) and the linear regression coefficient with time, the decadal change (called trend).

For the statistical analysis we used the pattern correlation approach, correlating the data

pairs (the respective geopotential height and ozone) at all gridpoints. The similarity of geopotential height and ozone perturbation maps was statistically analyzed for both climatology and trend in the northern hemisphere mid-latitude region (30° – 60° N; 252 grid points), separately for every month of the year. Because of the relatively high intraseasonal variability (e. g., Greisiger et al. 1998) a monthly analysis not a seasonal was chosen. From the pattern correlation, two coefficients are derived, namely the correlation coefficient, indicating the quality of the relation, and the regression coefficient, estimating the spatial linear relation of both quantities.

3. Results

An example of a wavy structure in geopotential height, and total ozone perturbations, is given in Fig. 1 for January, where wave number 2 is dominating. This Fig. 1 also illustrates

Fig. 1. Monthly mean deviations from zonal mean for midlatitudes of the northern hemisphere for January. Zero lines omitted, negative values dashed. Averaged over the period 1979–1992. (a) Total ozone from Nimbus 7 (TOMS). Contour interval 10 Dobson units. (b) Geopotential height at 300 hPa from NCEP reanalysis data. Contour interval 50 m.

the spatial similarity of both data sets in mid-latitudes of the northern hemisphere for the climatology. It can be realized easily, that large areas of positive geopotential height perturbations are situated at almost the same area of negative ozone perturbations, and vice versa.

We illustrate the used statistical method for two months (January and July), typical for winter and summer conditions. Figure 2 shows pattern correlation scatter diagrams, between geopotential height and ozone perturbation for the climatology (a, b) as well as for the trend (c, d) of January (a, c) and July (b, d). The relations are negative. In January the range of values is larger than in July. This was expected, because of the well-known higher activity of planetary waves in winter than in summer (see Fig. 4a). In the trend case, the larger range of values in winter compared to summer was also expected, because the interannual variability has more significant contribution in winter than in summer, which, in turn, is due to the higher activity of planetary waves in winter. In the climatology case, the correlation coefficients are -0.87 (-0.75) in January (July). In both months the correlation coefficients are significant with more than 99% after determination of the effective independent number of values, where autocorrelated values have been excluded (Taubenheim 1974; even in the worst case of all analyzed months there remain $N_{\text{eff}} = 49$ from 252 original grid points). Remarkably the resulting linear regression coefficients are similar in January and in July: -0.18 DU/m resp. -0.20 DU/m. In the trend case, the correlation coefficients are -0.68 (-0.76) in January (July) and are also significant with more than 99%, even with the lowest $N_{\text{eff}} = 63$ of all analyzed months. The linear regression coefficients are -0.13 (DU/10 years)/(m/10 years) for January, and -0.15 (DU/10 years)/(m/10 years) for July, again very similar in both months.

To study the annual variation of the relation between geopotential height, and total ozone perturbation, the linear regression coefficients are shown in Fig. 3 for the climatology (a) and the trend (b), as a function of months. In every month there exists a negative relation between the geopotential height and ozone perturbation, in the climatology as well as in the trend. In every month these regressions are statistically

Fig. 2. Pattern correlation scatter diagrams of geopotential height perturbation (300 hPa) (GH^*) and total ozone perturbation ($O3^*$) between 30° and $60^\circ N$ for January (a, c) and July (b, d); Upper panel: climatology values; lower panel: trend values. r is the correlation coefficient, b the regression coefficient. Linear regression is indicated by a straight line. (Original grid points: 252, N_{eff} means the number of effectively independent points).

significant, with more than 99% after Fisher's F-test. Further, the respective correlation coefficients vary between -0.93 and -0.68 (climatology) and -0.91 and -0.49 (trend), the significance of more than 99% results even with the worst N_{eff} given above. Thus, in extension to Peters and Entzian (1996, 1999), who showed this behavior for winter months and March,

we found a significant negative regression for all months of the year. To underline the annual variation, a polynomial of the 4th degree is drawn through the regression coefficients. Noticeable is the asymmetrical seasonal cycle with respect to the solstices, with higher amounts in spring than in autumn. Seasonal mean values for climatology-spring (MAM)

Fig. 3. Seasonal cycle of monthly regression coefficients b calculated from diagrams like in Fig. 2, for the climatology (a) and the trend (b). The 95% confidence intervals are added. The fitting curves are polynomials of the 4th degree.

are -0.20 DU/m, and for climatology-autumn (SON) are -0.15 DU/m. For the trend we find slightly lower values for the same months, spring -0.16 (DU/10 years)/(m/10 years) and autumn -0.09 (DU/10 years)/(m/10 years). Some spring and autumn confidence intervals (95%) do not overlap in the climatology and in the trend cases, so we may conclude that the seasonal differences between spring and autumn are also significant, i.e., the asymmetrical seasonal cycles in the climatology, and in the trend are real signals.

As annual averages we estimate -0.18 DU/m for the climatology, and -0.14 (DU/10 years)/(m/10 years) for the trend. By reducing this unit to DU/m, a general rule can be stated: 1 dam of geopotential height change, whether in space or time, will result in an opposite ozone perturbation of 1 to 2 DU.

4. Discussion

In summary, for the climatology and the trend, maps of longitude-dependent geopotential height (300 hPa layer), and total ozone perturbations, show anticorrelated patterns for each month in the period 1979–1992 in northern midlatitudes. The linear regressions are statistically significant for climatology and

trend, and have annually averaged values of -0.18 DU/m (climatology), and -0.14 DU/m (trend). The mean linear relation shows that a 1 dam increase (decrease) in geopotential height is equivalent to a 1–2 DU decrease (increase) in ozone. The fact that this regression holds for climatology, and trend in winter in the midlatitudes of the northern hemisphere, is already known from other studies (Hood and Zaff 1995; Peters and Entzian 1996). In addition, here we show that such a statistically significant relation of regression, also exists for all months of the year.

Based on large-scale wave transport model studies for winter (e.g., Peters et al. 1996) we expect the same transport process by planetary waves acting over the whole year. It is known that in summer the tropospheric activity of large-scale waves, is reduced by a factor of about 2 (Randel 1987), but nevertheless the westerly jet in the tropopause region is shifted to the North (45°N), and allows planetary waves to propagate westward and upward. The large-scale wave transport is concentrated between the middle troposphere, and the ozone layer maximum at about 70 hPa (18 km) (Peters et al. 1996). Of course, the larger amplitudes of the planetary waves in winter will

Fig. 4. Seasonal cycle a) 50°N-variance of the mean geopotential height at 300 hPa averaged over the period 1979–1989; the fitting curve is a polynomial of the 4th degree. b, c) Gradients (meridional: full line; vertical: dashed line) of zonal mean ozone volume mixing ratio; b) at 300 hPa and 45°N of only one year (1979); c) at about 100 hPa and about 45°N (for exact values see text), averaged over 11 years (1979–1989), the 95% confidence intervals are added, with a little offset in the lower curve to avoid overlapping. Note the different units.

cause larger ozone waves than in summer, as indicated in the scatter diagrams in Fig. 2. Especially for the climatology, our result of a significant annual pattern correlation between geopotential height and total ozone is supported by the result of Chen (1995). He studied the seasonal transport through the tropopause for the years 1985–1993. He also showed that

in summer stratosphere/troposphere exchange, is mainly due to quasi-stationary wave transport in the extratropics induced by the monsoon circulation. In similar studies with Eulerian and Lagrangian approaches, Appenzeller et al. (1996) and James et al. (2003) also found an asymmetric seasonal cycle in the mean exchange between stratosphere and troposphere

for midlatitudes. In addition, also for the trend we found an asymmetric seasonal cycle of the regression coefficients, with respect to the solstices with significantly higher amounts in spring, and lower amounts in autumn.

After the above mentioned linear models (Kurzeja 1984; Peters and Entzian 1999), two reasons are mainly responsible for the annual variability of large-scale wave transport of ozone, the annual variability of large-scale waves itself, and that of the zonal mean ozone gradients, the horizontal and the vertical. In Fig. 4a, it can be seen that the geopotential variance (here shown in 50°N and 300 hPa), has a symmetrical annual variation in relation to the solstices, in agreement with Randel (1987). To explain the asymmetry in the annual variation of the regression coefficient, we have to conclude that the other mentioned influence, that of the zonal mean ozone gradients, should give rise to that behavior. Indeed there exists an asymmetrical annual variation in the ozone gradients, as shown in Figs. 4b and c. Fig. 4b shows the meridional and vertical ozone gradients analyzed after McPeters et al. (1984), who determined ozone profiles from Nimbus 7 SBUV data for only one year (1979), but extrapolated them down to 500 hPa. From these zonal mean ozone profiles the meridional gradient of ozone at 300 hPa has been calculated between 30° and 60°N (representing 45°N), as well as the vertical ozone gradient between 503 and 179 hPa (log-mean at about 300 hPa) at 45°N. In Fig. 4c the ozone gradients are calculated from the mean ozone profiles of 11 years (1979–1989), but about 100 hPa (data from <http://code916.gsfc.nasa.gov/sbuv>). To avoid interpolation failures we used the given original data. So the meridional gradient has been calculated in 100 hPa between 27.5° and 57.5°N (representing 42.5°N), the vertical gradient has been calculated at 47.5°N between 100 and 70 hPa (representing 84 hPa). Both figures show, that the asymmetrical annual variation has a very stable structure with stronger gradients in spring and smaller in autumn. Thus the spatial structure variability of ozone perturbations over the year, is mainly determined by the advection through large-scale waves, but its intensity is obviously determined by the meridional and vertical gradients of the zonal mean ozone, i.e., high amounts of regression

coefficients exist, when strong ozone gradients are available. This holds for the climatology, as well as for the trend, as can be seen from Figs. 3a and 3b.

The proved annual variation of the regression coefficient between geopotential height and ozone perturbations for climatology and trend should be used for validation of global models and reanalyses.

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