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Longitude-dependent decadal ozone changes and ozone trends in boreal winter months during 1960–2000

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Abstract. This study examines the longitude-dependent decadal changes and trends of ozone for the boreal winter months during the period of 1960–2000. These changes are caused primarily by changes in the planetary wave structure in the upper troposphere and lower stratosphere. The decadal changes and trends over 4 decades of geopotential perturbations, defined as a deviation from the zonal mean, are estimated by linear regression with time. The decadal changes in longitude-dependent ozone were calculated with a simple transport model of ozone based on the known planetary wave structure changes and prescribed zonal mean ozone gradients.

For December of the 1960s and 1980s a statistically significant Rossby wave track appeared over the North Atlantic and Europe with an anticyclonic disturbance over the Eastern North Atlantic and Western Europe, flanked by cyclonic disturbances. In the 1970s and 1990s statistically significant cyclonic disturbances appeared over the Eastern North Atlantic and Europe, surrounded by anticyclonic anomalies over Northern Africa, Central Asia and Greenland. Similar patterns have been found for January. The Rossby wave track over the North Atlantic and Europe is stronger in the 1980s than in the 1960s. For February, the variability of the regression patterns is higher. For January we found a strong alteration in the modelled decadal changes in total ozone over Central and Northern Europe, showing a decrease of about 15 DU in the 1960s and 1980s and an increase of about 10 DU in the 1970s and 1990s.

Over Central Europe the positive geopotential height trend (increase of 2.3 m/yr) over 40 years is of the same order (about 100 m) as the increase in the 1980s alone. This is important to recognize because it implies a total ozone decrease over Europe of the order of 14 DU for the 1960–2000 period, for January, if we use the standard change regression relation that about a 10-m geopotential height increase at 300 hPa is related to about a 1.4-DU total ozone decrease.

Keywords. Meteorology and Atmospheric Dynamics (Climatology, Middle Atmosphere dynamics)

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1 Introduction

The assessment of the action of ozone chemistry, due to natural or anthropogeneous generated minor constituents at any location in the atmosphere, requires the knowledge of the dynamical-induced ozone variations. Many observational and model studies of the ozone change have dealt with the zonal mean ozone variability only, but for a decade the need to also study the structure of the longitude-dependent decadal ozone changes has become more and more the focus of investigations (e.g. Niu et al., 1992; Hood and Zaff, 1995; Peters and Entzian, 1996, 1999; Knudsen and Andersen, 2001; Hood and Soukharev, 2005). For instance, over Central Europe the total ozone change in January of the 1980s was twice as large as that of the zonal mean change (Niu et al., 1992). This means that the longitude-dependent part was of the same order as the zonal mean part. It was shown by Hood et al. (1995) and by Peters et al. (1996) that the decadal change in the large-scale wave structure in the geopotential height will cause the longitude-dependent decadal ozone change, due to different wave transport. The irreversible transport due to changing planetary waves dominates in the height region from the upper troposphere up to the ozone layer maximum (near 70 hPa$\sim$25 km) in the boreal winters of the 1980s. The seasonal variability of this transport in winter was shown by Peters and Entzian (1999). Hood et al. (1997) discussed the complex February structure explicitly. Knudsen and Andersen (2001) examined the springtime structure of the longitude-dependent decadal ozone change in more detail.

All in all, the longitude-dependent ozone changes have many implications, for instance, on the appearance of deep ozone miniholes by changing the monthly mean background concentration (James et al., 2000), on the dynamics by different feedback processes (Kirchner and Peters, 2003), on the zonal mean ozone trend by different wave transport (Hood and Soukharev, 2005), on the location of Rossby wave breaking events through an alteration of the background stream, or on the coupling of atmospheric layers (Gabriel et al., 2007) due to induced changes in planetary wave propagation.

The longitude-dependent ozone distribution has been unknown during the decades before the “First GARP Global Experiment” (FGGE) started in 1978/79. The results presented in this study are a first approximation of the zonally asymmetric structure of the ozone change unknown so far. In this study we extend our investigation over the whole period from 1959 up to 2001. With the help of a linear transport model for large-scale waves (Peters et al., 1996), we were able to calculate the decadal changes for all 4 decades. This was possible because the NCEP reanalyses data set (Kalnay et al., 1996, upgrades) covers this period. On the other hand, the influence of the zonal mean ozone change on the zonally asymmetric ozone is of a secondary order, as was shown by Peters and Entzian (1999). As a result, we obtain a three-dimensional distribution of the ozone change up to 10 hPa (about 30 km). In this report we focus on total ozone changes. Based on a regression analysis the annual zonally asymmetric relationship between total ozone and the 300 hPa geopotential was estimated by Entzian and Peters (2004). On average, they found an empirical relationship that about a 10-m geopotential height increase at 300 hPa is related to about a 1.4-DU total ozone decrease. Based on this relation the zonally asymmetric ozone trend from 1960–2000 was estimated from the zonally asymmetric 300 hPa geopotential trend. A comparison with the long-term series of total ozone from ground-based stations over Europe and with ERA-40 total ozone changes, where ozone was assimilated off-line, shows similar temporal and pattern changes.

In Sect. 2, the methods of calculation used are explained and in Sect. 3, we show the statistical and model results. In Sect. 4 a discussion is given, and the summary is presented in Sect. 5.

2 Data sets, statistics and method of ozone estimation

The data sets we used are the reanalyses of NCEP (Kalnay et al., 1996, upgrades) in a $1^\circ \times 1^\circ$ – latitude times longitude grid resolution, a sufficient resolution for our purpose, and the reanalysis (ERA-40) of ECMWF for data verification. The daily data relates to 00 universal time values at standard pressure levels up to 10 hPa. Further, we compared our results with total ozone from TOMS satellite measurements (version 8, Wellemeyer et al., 2004) and ERA-40 ozone assimilated off-line (Dethof and Holm, 2004).

For statistics, we used linear regression analyses with a 95% significance test for the deviation from the zero hypotheses which is sufficient for analyzing geophysical time series longer than decades (Taubenheim, 1969).

The transport model approach used is described in Peters et al. (1996) in detail. Here we give a short description of the basic assumptions. The model is based on the stationary quasi-geostrophic transport equation for the ozone mass mixing ratio η without any sources:

$$\frac{1}{a\cos\varphi}\frac{\partial \eta^*}{\partial \lambda} = \left(-\frac{v^*}{a}\frac{\partial \bar{\eta}}{\partial \varphi} - w^*\frac{\partial \bar{\eta}}{\partial Z}\right)\bar{u}^{-1}, \qquad (1)$$

where $Z{=}-H\ln(p/p_s)$ is the vertical coordinate, λ the longitude and ϕ the latitude; p is the pressure and p_s=1000 hPa, H is the scale height, a the Earth radius. (u, v, w) represents the velocity components. The bar means the zonal mean values and the star represents the deviation from it. v^* and w^* are related to the geopotential deviation, respectively. A Fourier decomposition of geopotential was used to calculate the wave contributions to η^* at different pressure layers, due to horizontal and vertical advection. The amplitudes and phases of the monthly mean geopotential, as well as the zonal mean fields were calculated from the above-mentioned reanalyses of NCEP.

The zonal mean ozone distribution of the Northern Hemisphere for mean winter conditions after McPeters et al. (1984) was used to estimate the zonal mean gradients needed in Eq. (1). As discussed in Peters and Entzian (1999), the variation of the zonal mean ozone distribution has only a weak influence on the zonally asymmetric ozone change in comparison to changes in the zonally asymmetric geopotential patterns.

All in all, based on 5-year averages of the zonally asymmetric geopotential, this allows us to calculate the zonally asymmetric ozone concentration at the beginning and at the end of a decade at each layer. The difference in both calculations represents the decadal zonally asymmetric ozone change. The column integral of it defines the decadal zonally asymmetric total ozone change.

3 Results

3.1 Decadal change

Figure 1 shows the decadal changes in the geopotential height of 300-hPa layers for December. In the 1960s and 1980s a Rossby wave track appeared over the North Atlantic and Europe with an anticyclonic disturbance over the Eastern North Atlantic and Western Europe, flanked by cyclonic disturbances. All disturbances are statistically significant in their centers except for the anticyclonic one in the 1980s. But the pattern of the 1980s looks quiet similar to the linear regression pattern estimated for the 1979–1992 TOMS period by Peters and Entzian (1999, their Fig. 2a), where all their

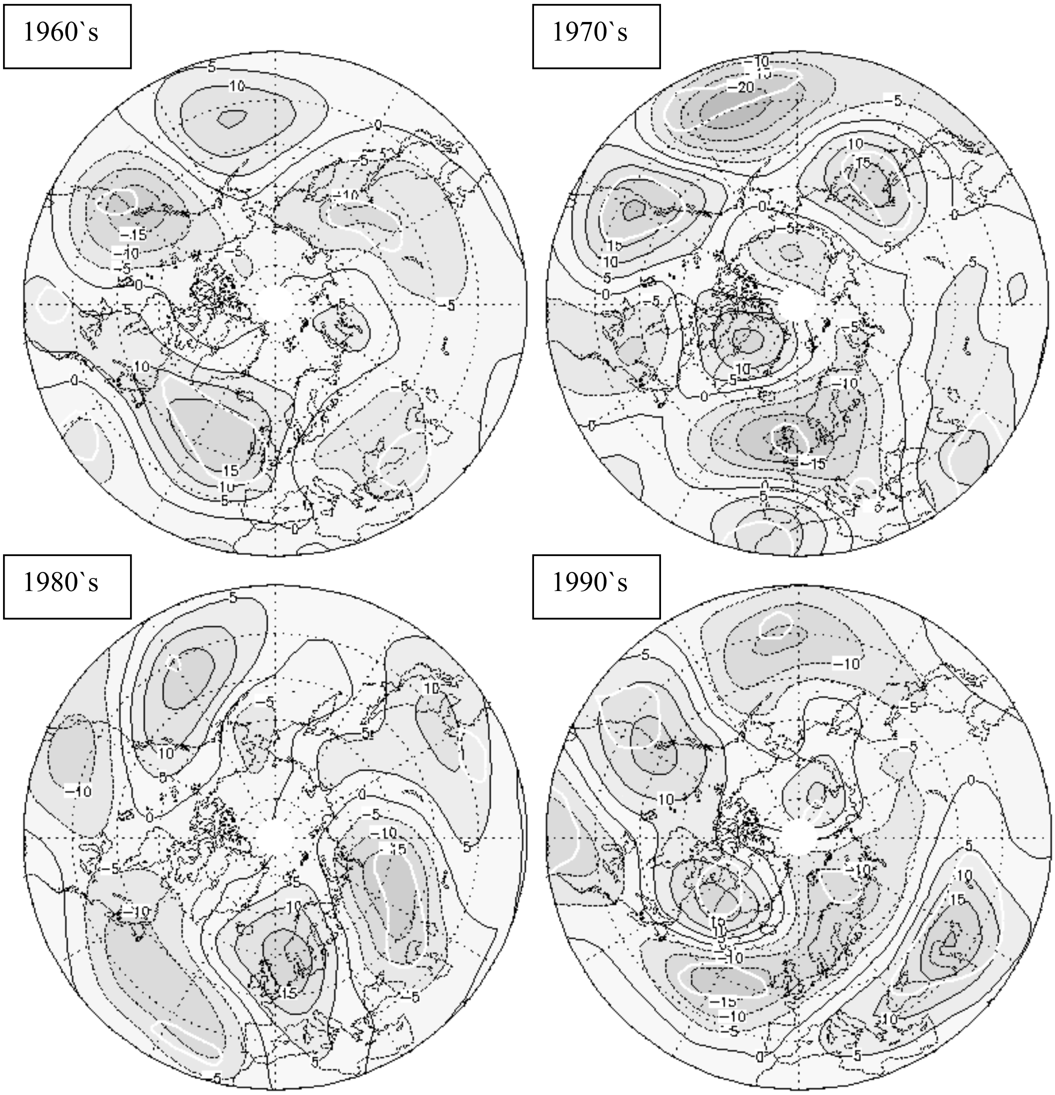

Fig. 1. Decadal change in mean geopotential height perturbations at the 300-hPa layer for December as linear regression with time (m/yr). White line encloses area of significance (>95%).

patterns were statistically significant due to the longer period. In the 1970s and 1990s statistically significant cyclonic disturbances appeared over the Eastern North Atlantic and Europe, surrounded by anticyclonic anomalies over Northern Africa, Central Asia and Greenland. A negative PNA (Northeast Pacific – North America) pattern occurred in the 1960s and 1980s and a positive one in the 1970s and 1990s (vice versa over Central North Pacific), which are partially significant.

The decadal change patterns for January are shown in Fig. 2. Similar patterns occurred for January as for December. The Rossby wave track over the North Atlantic and Europe is stronger in the 1980s than in the 1960s. The negative disturbance over Europe in the 1970s is also part of a Rossby wave train from the North Atlantic to Central Asia, but with inversed amplitudes, similar to those of the 1980s. The negative PNA pattern of January in the 1960s is shifted northwards in comparison to December. Some of the mentioned patterns are statistically significant. By comparing the January patterns of the 1980s with patterns for the 1979–1992 period (Peters and Entzian, 1999, their Fig. 2b) similar patterns were found with a statistically significant Rossby wave train over the North Atlantic and Europe, due to the longer period.

For February (Fig. 3), the variability of the regression patterns is stronger. A statistically significant Rossby wave train was found over the North Atlantic and Europe in the 1960s and 1990s, with different curvatures of the wave trains. In February of the 1970s a dipol pattern occurred over the North Atlantic (related to the change in NAO pattern) and over

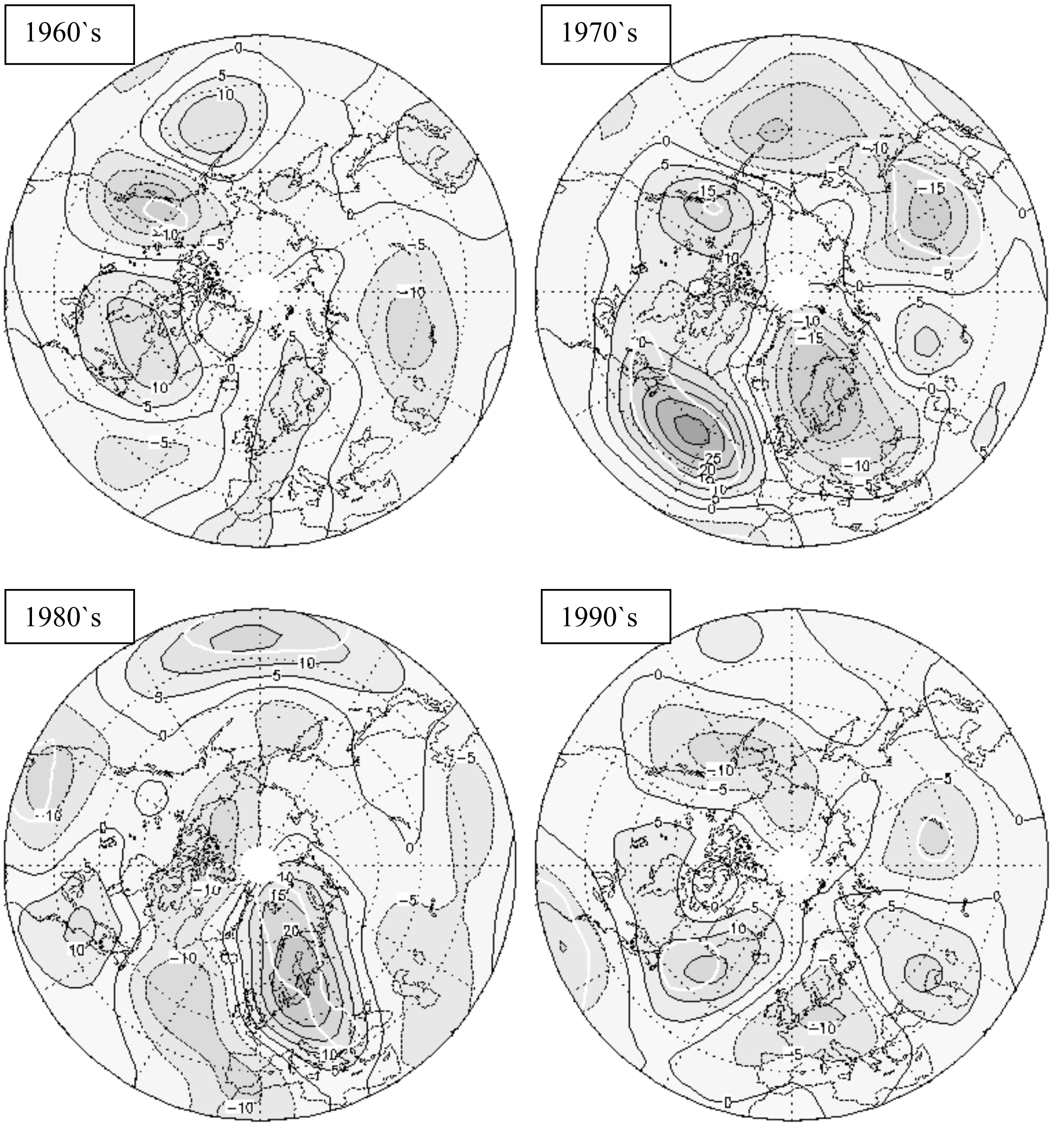

Fig. 2. Same as Fig. 1, but for January.

Siberia. In February of the 1980s a negative PNA pattern appeared and over the northern part of the North Atlantic a strong cyclonic disturbance occurred. In comparison with regression patterns of the TOMS period (1979–1992) shown by Peters and Entzian (1999, their Fig. 2c), no related statistically significant sea-saw pattern was found over the Western North Atlantic.

All in all, the December and January decadal change patterns are similar, but for February a stronger variability in the patterns was found, so no winter mean seems to be appropriate.

An independent regression analyses with the ERA-40 data set, using the monthly mean 300-hPa geopotential height, shows similar wave trains and patterns of changes for each of the winter months during all 4 decades from 1960–2000 (here not shown).

3.2 Model estimation of decadal ozone changes

By using the method of Peters et al. (1996) (a short description of the model configuration is given in Sect. 2), we calculated the decadal total ozone changes as a function of the decadal differences of 5-year averages (end minus beginning of the decade) of all available geopotential heights up to 10 hPa with prescribed zonal mean ozone gradients. In this section we focus on the January results because the decadal January change in the 1980s was similar to December (Peters and Entzian, 1996).

In Fig. 4 the decadal January differences of 5-year averages of geopotential height perturbation at the 300-hPa layers are shown. The differences should be divided by 10 years, in order to obtain the same time scale as shown in Fig. 2. If we compare these differences with the linear regression

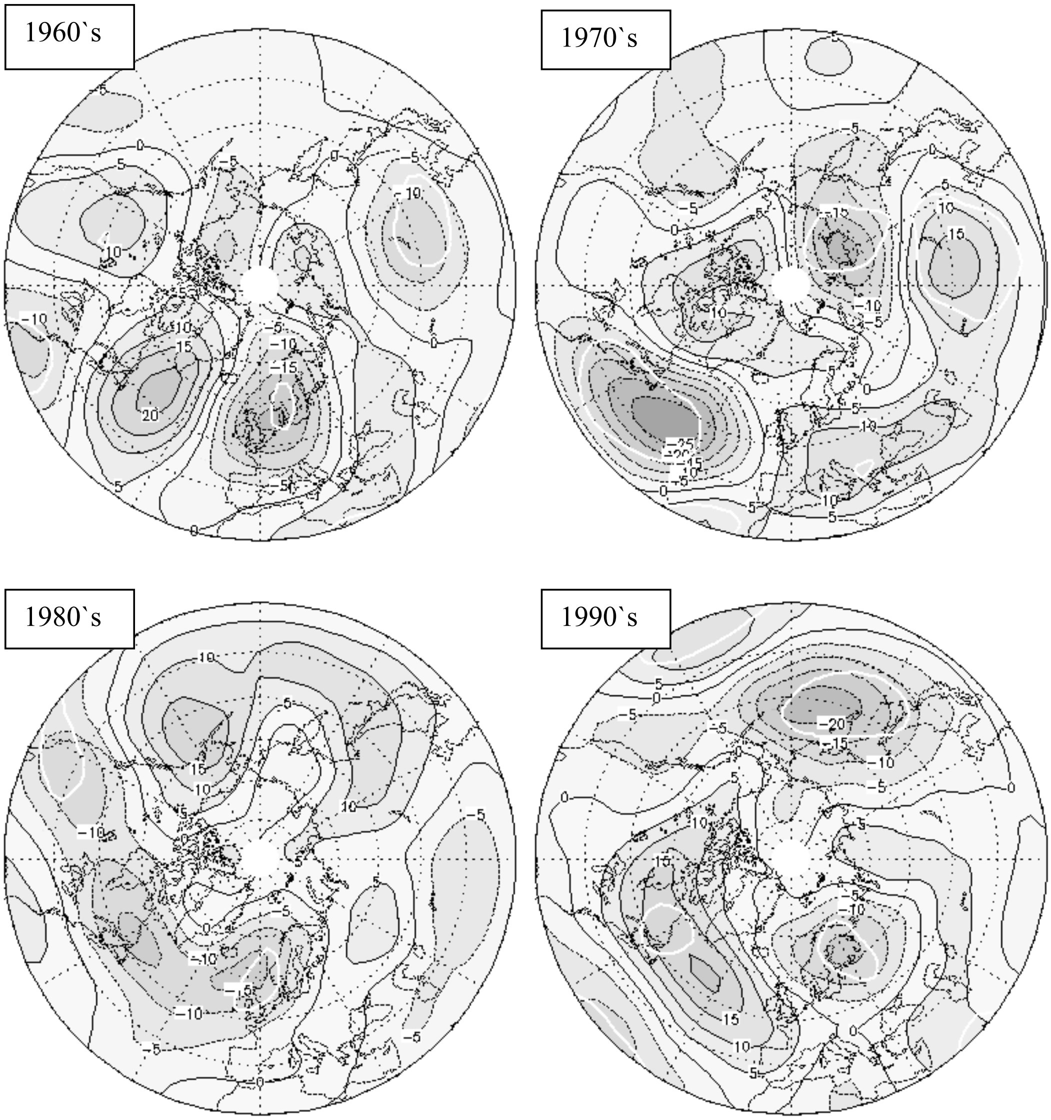

Fig. 3. Same as Fig. 1, but for February.

estimates (Fig. 2) for each decade we find a good agreement between related images. We conclude that the decadal January differences of the 5-year averages are a first approximation of the linear regression patterns. In particular, the Rossby wave tracks in the decadal changes over the North Atlantic and Europe, and over the Pacific and North America are well captured.

The calculated decadal January total ozone changes are shown in Fig. 5. In the 1960s and 1980s a decrease in the total ozone of about 15 DU was found over Central Europe and Northern Europe but in the 1970s and 1990s there was an increase of about 10 DU; however, over the North Atlantic it was vice versa. A strong total ozone decrease occurred over the North Atlantic in the 1970s and a strong increase in the 1980s. Over North America a total ozone increase was found in the 1960s and 1980s but a decrease occurred in the 1970s and 1990s. A strong increase was found over Western North America in the 1960s and over the Pacific Ocean in the 1970s. Over Siberia a strong ozone decrease in the 1980s appeared and an increase occurred in the 1990s. The strongest decadal changes over the North Atlantic and European region occurred in the 1970s and 1980s. For these decades, in Fig. 6 altitude – longitude cross sections at 50° N are shown. The main contribution to the decadal total ozone changes came from the height region between 500 hPa and 70 hPa (ozone layer maximum). For the 1970s the strongest ozone decrease occurred over the North Atlantic and the strongest increase occurred over the Pacific in the same height region. The ozone decrease over the North Atlantic continued in the middle stratosphere between 70 hPa and 10 hPa which also

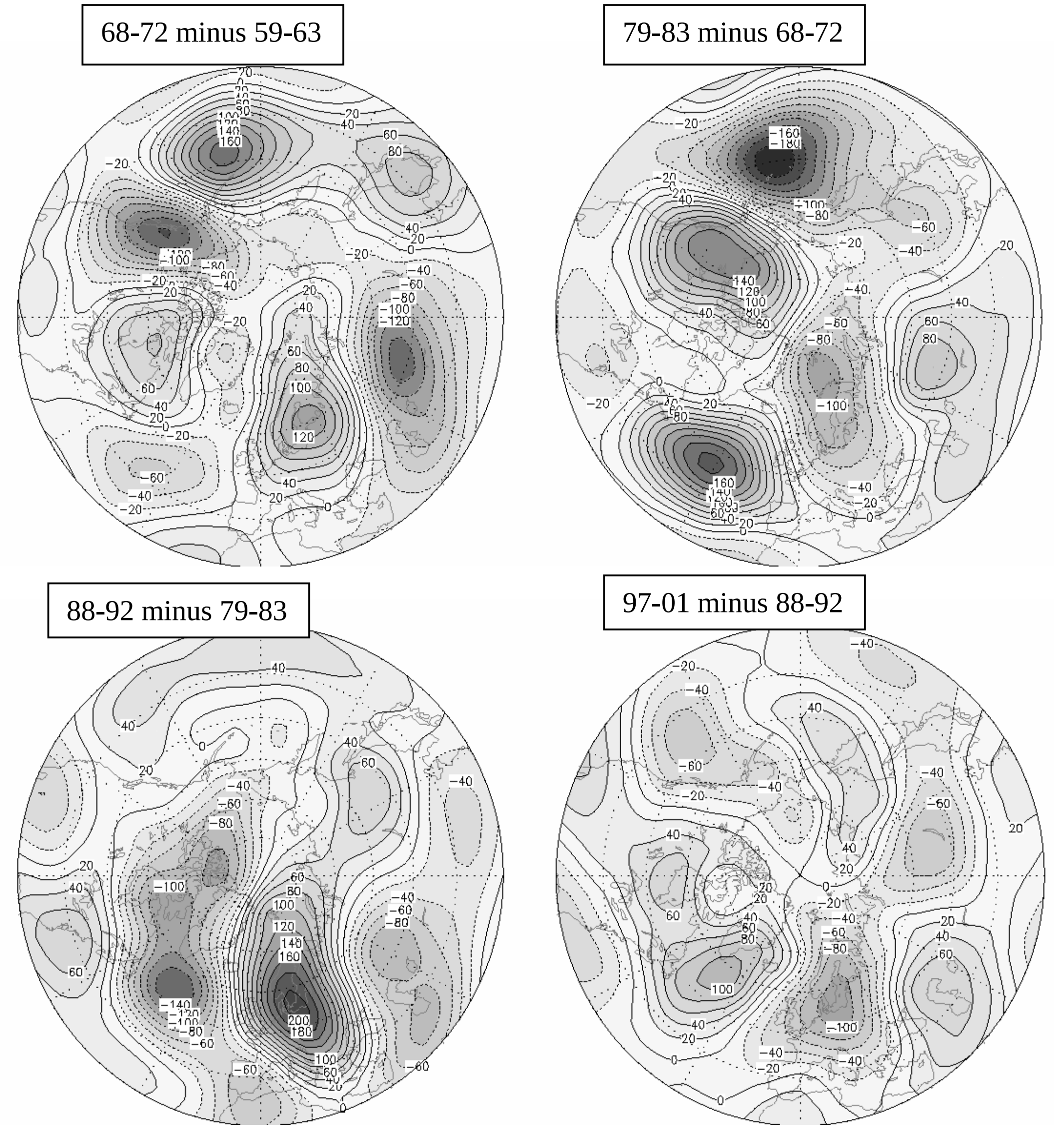

Fig. 4. Decadal January differences of 5-year averages of mean geopotential height perturbations (end minus beginning of the decade) (m) at the 300-hPa layer.

contributes to the total ozone decrease. In the 1980s the main contribution is concentrated over the North Atlantic, Europe and Asia. Especially over the North Atlantic, the increase covered the whole height region. The decrease over Central Europe is restricted to the upper troposphere and lower stratosphere. In the middle atmosphere we found a weaker influence of the decadal geopotential height perturbation changes in the total ozone changes than in the upper troposphere and lower stratosphere, as expected.

Similar calculations have been done for December and February (not shown) revealing the strong anticorrelation of the total ozone to the 300-hPa geopotential height patterns, which we have expected from former calculations (e.g. Peters and Entzian, 1999) and from the known strong empirical regression relationship (Entzian and Peters, 2004).

The decadal changes in the total ozone perturbation for the 1980s and for the 1990s have been checked against observations of the TOMS satellite measurements by Nimbus 7 and by Earth Probe (version 8, Wellenmeyer et al., 2004). We found good agreement between those measurements and the model results of decadal total ozone changes in the Northern Hemisphere. Detailed discussions of this strong relationship can be found in Peters et al. (1996) and Peters and Entzian (1999).

Further, we compared our results with the decadal ERA-40 total ozone change in January (not shown). We found good

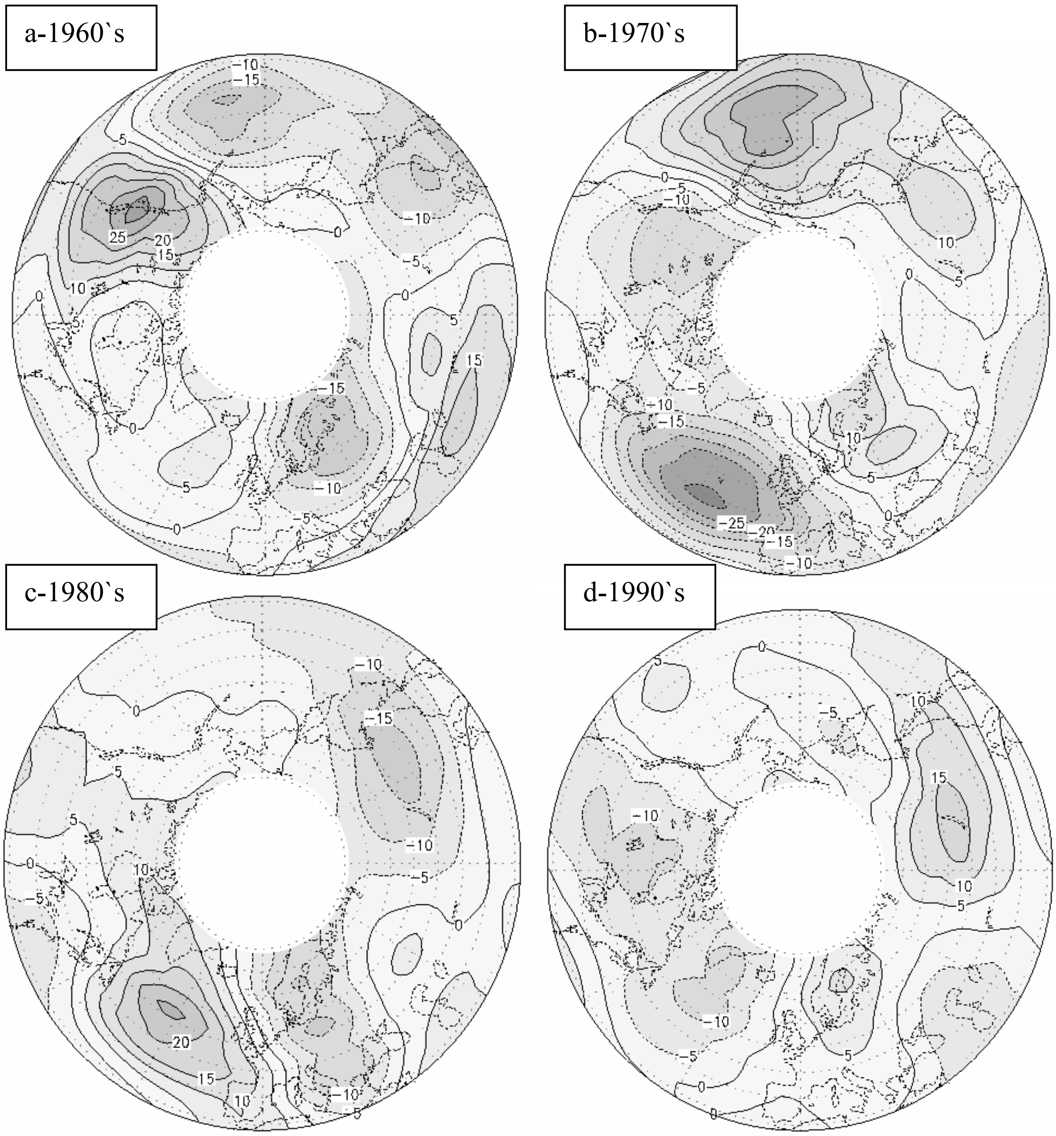

Fig. 5. Model results of mean decadal change in total ozone (DU) for the 1960s **(a)**, 1970s **(b)**, 1980s **(c)** and 1990s **(d)** calculated with differences of 5-year averages (end minus beginning of the decade) of geopotential heights for January.

agreement for the significant decadal change patterns over the North Atlantic – European region for all decades. There exist differences outside this region, which are discussed in Sect. 4.

3.3 Trend

In order to reveal the trend patterns during the 1960–2000 period, an empirical regression is used to estimate the total ozone change, because the simple adiabatic transport model ansatz without any sources does not work for such a long time over 40 years. For this reason, we first calculate the geopotential height trends at 300 hPa and by using the known strong empirical relationship for the TOMS period (Entzian and Peters, 2004), an estimation of the zonally asymmetric total ozone trend structure was possible.

In Fig. 7 the geopotential height trends at 300 hPa and 70 hPa during the 1960–2000 period are shown. In December, a significant increase in the trend occurred over Europe, flanked by negative trends over the North Atlantic and Ural. In January we found a statistically significant increase in the trend at 300 hPa over Central and Northern Europe, a dipol pattern over the North Atlantic (like NAO pattern), an increase over Western Canada and a decrease over Alaska and Pacific ocean (like PNA pattern). The Canada and Greenland patterns continue in the 70 hPa layer and are significant due to the stronger winter conditions. In February, we found a significant sea saw pattern over the North Atlantic,

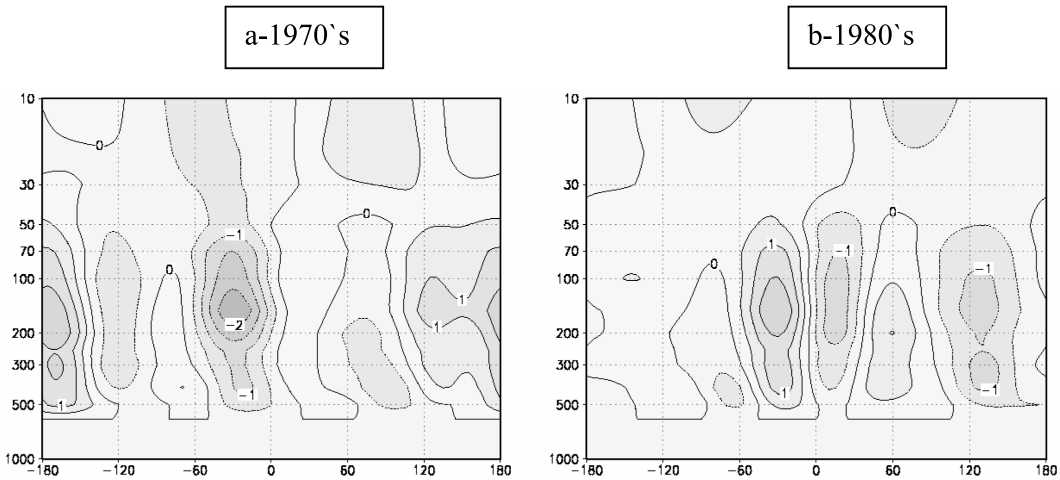

Fig. 6. Altitude-longitude cross section of modelled ozone distribution (DU km^{-1}) at 50° N latitude for January.

an increase over North America and a decrease over the Far East. In the 70-hPa layer the North America pattern is still significant as well as the Far East pattern. The negative trend over Greenland is not significant. A comparison with the ERA-40 geopotential height change in 300 hPa and 70 hPa (not shown) reveals similar structural changes.

By using a constant mean negative empirical relationship for all extra tropical latitudes and longitudes of the Northern Hemisphere (−1.4 DU/10 m, Entzian and Peters, 2004) we obtain an inverse structure for the zonally asymmetric total ozone trend in comparison to the geopotential height change. A comparison with the ERA-40 zonally asymmetric ozone trend patterns (not shown) reveals similar patterns for December and January but shows stronger differences in February. Over Central Europe the zonal mean total ozone trend values of ERA-40 data are about −0.4 DU/yr for December, −0.6 DU/yr for January and −0.2 DU/yr for February, where the values in December and January are significant. For these values, the estimated regression values are of the order of 60%, but the agreement with the position and structure of the patterns was good. This is discussed in Sect. 4.

In the next section, for the significant trend regions over the North Atlantic – European region, we examined total ozone trends derived from geopotential height trends at 300 hPa and compared, where possible, those with ground-based stations measurements of Central Europe.

3.4 Ozone trends over the North Atlantic – European region

At the centre of significance (Fig. 7a, 40° N, 10° E) the annual December variability of the 300-hPa geopotential perturbation is shown for the period 1959–2001 in Fig. 8, together with an 11-year running mean and the linear regression line with time. We found a decrease in the 1970s and 1990s but an increase in the 1960s and 1980s, reflecting the results obtained in Sect. 3.1. The linear regression value is about 2 m/yr, resulting in a −0.26 DU/yr total ozone decrease by using the empirical relationship of −0.13 DU/m for January (Entzian and Peters, 2004). Ground-based measurements of Arosa, Hohenpeissenberg and Potsdam during this period show linear regression values of about −0.8 DU/yr, where the amount is three times larger. This difference is related to the zonal mean trend which was not included in the estimation of the regression value.

The monthly mean January values of significant geopotential height perturbations over Central Europe (50° N, 10° E) at the 300-hPa layer are plotted in Fig. 9a for the period 1960–2002. They show a high variability of about 150 m. Nevertheless, a decadal change defined by an 11- year running mean can be identified, i.e. an increase in the 1960s and 1980s and a decrease in the 1970s and 1990s. The trend of geopotential height is of the order of a 2.5-m/yr increase, corresponding to a −0.32-DU/yr decrease in total ozone, but for Labrador we found an increase in ozone in the same order of 0.32 DU/yr. Due to the different wave transport, a large difference between Europe and Labrador occurred (Peters and Entzian, 1999). The total ozone trend for Arosa, Hohenpeissenberg and Potsdam is about −0.87 DU/yr, again the amount is about three times larger, because the zonal mean ozone trend was included.

4 Discussion

This study focuses on the zonally asymmetric changes and the trend of total ozone, which are induced by changes in the planetary wave structure in the upper troposphere and lower stratosphere. The decadal zonal mean total ozone change and trend is excluded. The changes in the large-scale wave structure may be caused by natural variability or by anthropogenically-induced circulation changes. How these

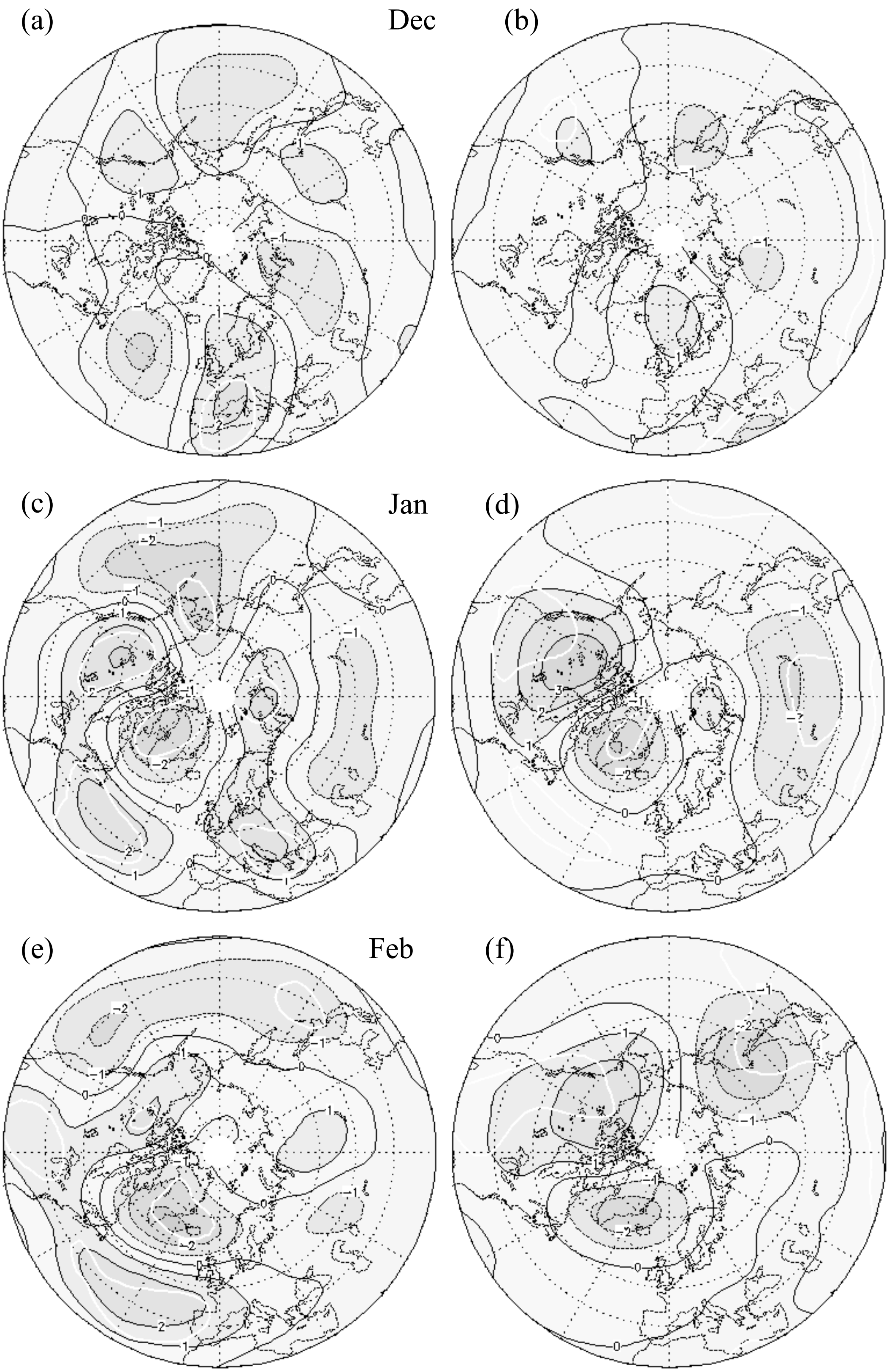

Fig. 7. Mean geopotential height trends at 300 hPa (left column) and at 70 hPa (right column) for winter months during the 1960–2000 period, for December **(a, b)**, January **(c, d)**, February **(e, f)**.

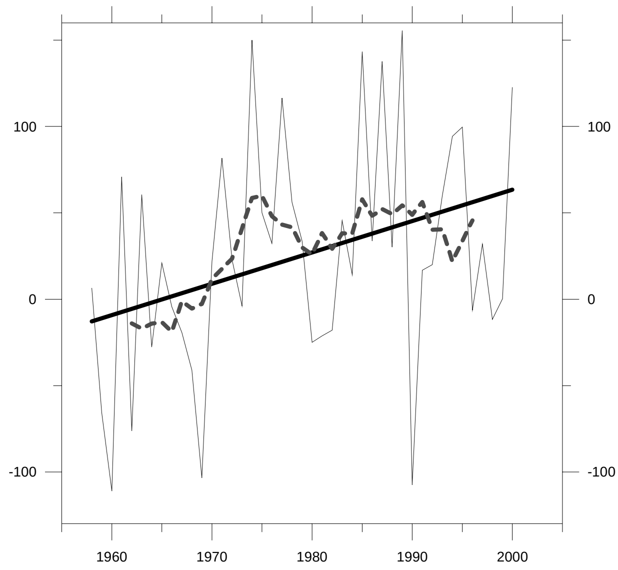

Fig. 8. Regional evolution of mean geopotential height perturbations (m) over Southern Europe (40° N, 10° E) at the 300-hPa layer for December. Linear regression with time (trend, straight line) and 9-year running mean (decadal change, dashed line).

planetary wave changes are related to the global warming scenario is still an open question and the subject of many research studies. However, some studies (e.g. Gabriel and Schmitz, 2003; Hood and Soukharev, 2005) investigate the important role of zonally asymmetric wave flux and ozone wave transport for interannual zonal mean ozone variability, indicating that about 50% of the zonal mean ozone depletion in the Northern Hemisphere is dynamical induced and about 50% is related to changed ozone chemistry. Further, it seems that the long-term trend of zonal mean ozone undergoes a change or weakening in the 1990s (e.g. Steinbrecht et al., 2004; Rosenfield et al., 2005).

We compare the geopotential decadal change and geopotential trend of the winter months between NCEP reanalysis and ERA-40 reanalysis. For both projects the agreement of the structure changes of the 300-hPa geopotential patterns was very good, which was expected, due to the focus on large-scale changes in the monthly means.

The fact that the simple transport model and methodology of ozone calculations works quite well for the TOMS-1978–1992 period was explicitly discussed in Peters and Entzian (1999), to which we refer here. In this paper we already found differences between model and observations over Siberia and the Pacific Ocean which could be related to model assumptions. The influence of parameterized chemistry and diabatic heating effects on such a wave transport model was shown by Nathan and Li (1991). In the future, those model improvements should be included in order to capture the middle and upper stratosphere influence. Nevertheless, the ozone patterns changes induced by upper tropospheric and lower stratospheric planetary wave changes are well captured by the transport model used here.

For December and January we found over the North Atlantic European region similar structural changes, but the one for February differs, due to the high variability during the winter-spring reversals, which results in a weaker significance.

The ozone trend is empirically determined because the zonal mean ozone field before the 1980s is unknown. In comparison to the ERA-40 off-line assimilated ozone we gained about 60% of the maxima and minima, but the agreement with the position and structure of patterns was good.

The ground-based total ozone measurements included in their local trend some effects discussed in many papers (e.g. a review up to 2001 was given by Staehelin et al., 2001; Steinbrecht et al., 2003; Rosenfield et al., 2005). The planetary wave contribution at Hohenpeissenberg in southern Germany amounts to 25% (Steinbrecht et al., 1998), which is in agreement with our results shown in Sect. 3.4.

The extension of our method to other well defined time intervals of observation is easy to realize, but we need another 20 years (or more) of observation, in order to examine the turnaround discussed in the literature, with a focus on longitude dependent ozone structure changes (e.g. Hadjinicolaou et al., 2005).

5 Summary

We examine the longitude-dependent decadal changes and trends of ozone for the boreal winter months during the period of 1960–2000. These changes are caused primarily by changes in the planetary wave structure in the upper troposphere and lower stratosphere. The decadal changes and trends over 4 decades of geopotential perturbations, defined as the deviation from zonal mean, are estimated by linear regression with time.

For December of the 1960s and 1980s a statistically significant Rossby wave track appeared over the North Atlantic and Europe with an anticyclonic disturbance over the Eastern North Atlantic and Western Europe, flanked by cyclonic disturbances. In the 1970s and 1990s statistically significant cyclonic disturbances appeared over the Eastern North Atlantic and Europe, surrounded by anticyclonic anomalies over Northern Africa, Central Asia and Greenland. A negative PNA pattern occurred in the 1960s and 1980s and a positive one in the 1970s and 1990s. Similar patterns have been found for January. The Rossby wave track over the North Atlantic and Europe is stronger in the 1980s than in the 1960s. The negative PNA pattern of January in the 1960s is shifted northwards in comparison to December. For February, the variability of the regression patterns is higher. A statistically significant Rossby wave train was found over the North Atlantic and Europe with different curvatures in the 1960s and 1990s. In February of the 1970s a sea-saw pattern occurred

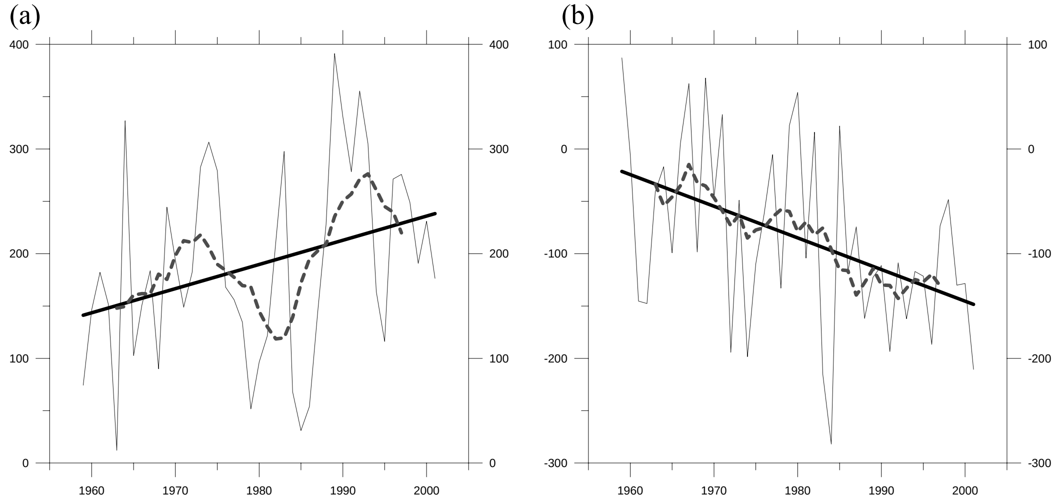

Fig. 9. Same as Fig. 8 over Central Europe (50° N, 10° E) **(a)** and Labrador **(b)** at for January.

over the North Atlantic (which may be related to changes in NAO) and over Siberia, but in comparison with regression patterns of the TOMS period over 1979–1992 no related statistically significant dipol pattern existed over the Western North Atlantic, due to the different time interval.

The decadal zonally asymmetric ozone change was calculated with a simple transport model of ozone based on the known planetary wave structure changes and prescribed zonal mean ozone gradients. For December and January we found a strong alteration in the modelled decadal changes of total ozone over Central and Northern Europe, with a decrease of about 15 DU in the 1960s and 1980s and an increase of about 10 DU in the 1970s and 1990s. The calculated longitude-dependent total ozone change for all decades was verified with ERA-40 reanalysis of the total ozone and for the last two decades with that of TOMS-satellite measurements. In December and January of all decades we found a good agreement of total ozone patterns over the North Atlantic European region. For all decades there exist differences between model and observations over Siberia and the Pacific Ocean which we relate to the model's simplifications, for instance, changes in ozone chemistry are not included.

Based on a regression analysis the annual zonally asymmetric relationship between total ozone and the 300 hPa geopotential was estimated by Entzian and Peters (2004). On average, they found an empirical relationship that about a 10-m geopotential height increase at 300 hPa is related to about a 1.4-DU total ozone decrease. Based on this relation the zonally asymmetric ozone trend from 1960–2000 was estimated from the zonally asymmetric 300 hPa geopotential height trend. Over Central Europe the positive geopotential trend (increase of 2.3 m/yr) for 40 years is of the same order (about 100 m) as the increase in the 1980s alone. The longitude-dependent total ozone trends of 1960–2000 were compared with ERA-40 total ozone and ground-based station measurements over Central Europe. We found a decreasing trend of zonally asymmetric total ozone in good agreement with ERA-40 data set. The ground-based measurements of total ozone trends (amounts) are nearly three times larger for December and January, but the difference to ground-based stations over Europe is related mainly to the zonal mean ozone trend, not included in the empirical relationship.

The zonally asymmetric total ozone over Europe implies a zonally asymmetric total ozone decrease of about 14 DU over Europe in December and January for the 1960–2000 period, similar to the planetary wave induced change of the 1980s alone.

The identification of zonally asymmetric ozone change patterns, as induced by changes in the large scale-dynamics, is important for the search of suitable proxies needed in the total ozone change analysis (for instance, Jrrar et al., 2006; Maeder et al., 2007).

The longitude-dependent decadal changes and the trend of total ozone could have strong influences and implications on dynamical processes, via feedback processes which are the subject of future research.

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