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Long-term trends in the middle atmosphere dynamics at northern middle latitudes – one regime or two different regimes?

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Abstract

Due to increasing atmospheric concentration of greenhouse gases and changing stratospheric ozone concentration, both of anthropogenic origin, various quantities in the middle atmosphere reveal long-term changes and trends. Lastovicka and Krizan (2006) indicated possibility of change of trends in the dynamics in the northern midlatitude middle atmosphere as a whole in the 1990s. To search for such change of trends we use data on winds in the mesopause region, on total columnar ozone, on ozone laminae, on winds in the middle and lower stratosphere, and on peak electron density in the E region of the ionosphere. One group of quantities, the mesopause region wind-like trends, changes their trends around 1990, the other one, the total ozone-like trends, in the mid-1990s. Altogether they create a skeleton of scenario of the change of the middle atmosphere dynamics trends in the 1990s. Drivers of these changes appear to be different for the first group and for the second group. Tropospheric processes seem to play a role in the changes of trends in middle atmospheric dynamics.

1 Introduction

Human activities affect the atmosphere by pollution since the beginning of industrial revolution. This man-made anthropogenic forcing influences the atmosphere not only in the troposphere, its influence is detectable even in the thermosphere, up to heights of several hundred kilometres above surface, and changes climate in the whole atmosphere (e.g., Lastovicka et al., 2006). Life on Earth is more directly affected by climate change near the surface than in the middle and upper atmosphere, but as the story of the Earth's ozone layer illustrates, changes at higher levels of the atmosphere may be important for life on Earth, as well.

In the middle atmosphere, the stratosphere, mesosphere and lower (and/or lowermost) thermosphere, the two main anthropogenic drivers of long-term changes and trends are greenhouse gases (mainly carbon dioxide) and ozone, and some role is also played by water vapour concentration changes. As concerns CO_2, its increase in the middle atmosphere results in cooling, not heating of the middle atmosphere. The transition region between the CO_2 heating in the troposphere and cooling above is the tropopause region and the lowermost stratosphere. In the middle atmosphere, the radiative effect of CO_2 becomes more pronounced and produces a cooling. At these altitudes, CO_2 is optically thin and is unable to contain sufficiently outgoing infrared radiation; thermal energy is transferred by collisions with ambient gas to the excited states of CO_2 molecules and then lost to space via their infrared radiation. The ozone depletion, developed mainly in the 1980s and 1990s, reduced ozone absorption of solar UV radiation and, thus, contributed significantly to cooling of the stratosphere. However, reduction of stratospheric ozone concentration affects also higher levels, including the ionosphere and neutral atmosphere at the ionospheric E-region maximum heights (~110 km) (e.g., Akmaev et al., 2006; Bremer, 2008). Thus the whole middle atmosphere is directly or indirectly affected by stratospheric ozone depletion.

Cooling of the stratosphere was reviewed by Ramaswamy et al. (2001) and recently updated by Randel et al. (2009). They found some cooling in the whole stratosphere. Its main driver in the lower stratosphere is ozone depletion, whereas in the middle and upper stratosphere both ozone and greenhouse gases play an important role. Temperature trends in the mesosphere and mesopause region were reviewed by Beig et al. (2003). The mesosphere was found to be cooling by 2–3 K/decade, while in the mesopause region no significant temperature trend was observed, particularly in summer. Such height dependence of temperature trends in the mesosphere-lower thermosphere (MLT) region has been qualitatively confirmed by model simulations (e.g., Fomichev et al., 2007; Garcia et al., 2007).

A scenario of trends in the mesosphere, thermosphere and ionosphere was created by Lastovicka et al. (2006, 2008). This scenario provides a consistent pattern of change of the upper atmospheric climate in terms of long-term trends of selected upper atmosphere-ionosphere system variables. Recent progress in this area has been reviewed by Lastovicka (2009). Now it is right moment to investigate if (and how deep into) the stratosphere can “join” this scenario or it behaves in a separate manner as a consequence of different relative role of long-term change drivers, particularly of ozone. The results of this study contribute to such a goal.

When atmospheric temperature and its height profile change, we can expect changes in winds and activity of atmospheric waves. However, when Lastovicka et al. (2006, 2008) established the first scenario of trends in the mesosphere, thermosphere and ionosphere, they found three main areas of discrepancies, problems or unclear trends; one of them was the MLT region dynamics, where trends in winds at northern higher middle latitudes revealed a reversal near 1990. On the other hand, it is known that the total columnar ozone at northern middle latitudes changed its trend in the mid-1990s (e.g., Andersen et al., 2006; Harris et al., 2008; Krzyscin, 2006; Reinsel et al., 2005; Staehelin et al., 2001). Angell and Free (2009) claim based on Umkehr and ozone sonde data that the lower stratosphere (heights 10–19 km) contributes about half of the recent total ozone increase in northern moderate latitudes. The ozone trends in the lower stratosphere over Payerne (46.49° N, 6.57° E) at altitudes below 20 km were found to be caused, to a substantial extent, by dynamical changes (Weiss et al., 2001). Importance of dynamics in the turnaround of ozone trends in the mid-1990s was stressed also by, e.g., Krzyscin (2006) and Reinsel et al. (2005). There are various possible dynamical contributors to the long-term trend in total ozone, as discussed, e.g., by Staehelin et al. (2001) and Hudson et al. (2003). Thus it is possible that the whole middle atmospheric dynamics changed trends around the first half of the 1990s, as it was first tentatively mentioned by Lastovicka and Krizan (2006).

The main aim of the paper is to answer the question if long-term changes in the middle atmosphere (mesosphere and stratosphere) dynamics form one single regime of change, or if the dynamics in the upper and lower parts of the middle atmosphere display long-term changes governed by two different regimes/dominant drivers. As we show in the paper and as it is indicated by section titles/topics, there are rather two different regimes but these are not strictly associated with/divided by altitude.

The primary open problem of the scenario of long-term changes and trends in the mesosphere-thermosphere-ionosphere system is the atmospheric dynamics and atmospheric wave activity. The paper contributes to some extent also to this problem.

Section 2 describes the data and methods used. Section 3 treats ozone-like changes in other variables. Section 4 describes the MLT wind-like changes in trends in various variables. Section 5 contains brief discussion of observational results, and Sect. 6 is conclusions.

2 Data and methods

We deal with total columnar ozone, ozone laminae, stratospheric winds, MLT region winds and the maximum E region electron density represented by the critical frequency foE derived from ionosonde measurements. Information on trends in total columnar ozone are taken from literature, we do not analyze data. For other variables we deal with data, applying only very simple methods to get trends like direct comparison of data, linear fit or piecewise linear trend determination approach. Studied trends are mostly strong enough and evident to allow such simple approach.

Ozone laminae are narrow layers of significantly enhanced (positive laminae) or significantly depressed (negative laminae) ozone concentration in ozone profiles. The best height resolution ozone profiles are provided by ozonesondes, therefore we use European ozonesonde data. Long-term trends in the overall ozone content in laminae per profile are quite similar in Europe, Canada and northern Japan (Krizan and Lastovicka, 2005) therefore European data may be considered representative for northern higher middle latitudes. Trends based on positive laminae and on negative laminae are very similar (Krizan and Lastovicka, 2005) and positive laminae provide better and less noisy data, therefore here we use only positive laminae.

Ozone laminae are defined and derived in various ways, which are in more detail discussed, e.g., by Krizan and Lastovicka (2004, 2005, 2006). Here we use only positive laminae defined by enhancement of ozone concentration with respect to undisturbed ozone profile expressed in ozone partial pressure (nbar). We do not use lamina definition based on ozone mixing ratio. Two types of laminae are considered, large laminae with peak values more than 40 nbar above the undisturbed values, and small laminae with peak values between 10–20 nbar above the undisturbed values. Their predominant origin is different.

Ozone laminae are derived from ozonesonde ozone profiles measured at European stations Payerne (46.49° N, 6.57° E), Hoheinpeissenberg (47.8° N, 11.02° E), Lindenberg (52.21° N, 14.12° E), Legionowo (52.4° N, 20.97° E), Prague-Libus (50.02° N, 14.45° E), Uccle (50.8° N, 4.35° E). Station Prague-Libus made soundings only in January–April, other stations did it throughout the year. Payerne, Hohenpeissenberg and Uccle data were taken from 1970, whereas continuous measurements at Lindenberg began in 1975 and at Legionowo and Prague-Libus in 1979. Ozonesonde data were taken from Toronto database: http://www.msc-smc.ec.gc.ca/woudc.

Velocity and direction of stratospheric winds at pressure levels of 100, 50 and 10 hPa were taken from ERA-40 for the extra-tropical northern latitudes. Only selected results for 100 and 10 hPa are presented in the paper.

Mesopause region winds are used as measured at Collm (52° N, 15° E) by drift method, at Obninsk near Moscow (55° N, 37° E) by meteor radar (both with typical heights 90–95 km), and partly at Juliusruh (54.6° N, 13.4° E) by MF radar; results are taken from other papers.

Information on the behaviour of stratospheric planetary wave activity is taken from paper by Jacobi et al. (2009).

Ionospheric parameters are used as measured at the two most reliable European ionosonde stations Juliusruh (54.6° N, 13.4° E) and Slough/Chilton (51.6° N, 1.3° W). Data are taken from the Rutherford-Appleton Laboratory database: http://www.ukssdc.ac.uk/wdcc1/wdc_menu.htm.

3 Total ozone-like changes in trends

It is known that the total columnar ozone at northern middle latitudes reversed its trend in the mid-1990s (e.g., Andersen et al., 2006; Harris et al., 2008; Krzyscin, 2006; Reinsel et al., 2005; Staehelin et al., 2001). Figure 1 illustrates this change for grid point 45° N, 15° E based on Version 8 TOMS/SBUV total ozone satellite data. After a decrease since 1979 modulated by solar cycle responsible for the mini-peak near 1989, the total ozone trend reversed to increase in 1994–1995. Thus turnaround of total ozone trends occurs in the mid-1990s. The ozone trends in the lower stratosphere over Payerne (46.49° N, 6.57° E) at altitudes below 20 km were found to be caused, to a substantial extent, by dynamical changes, including the turnaround of trends in the mid-1990s (Weiss et al., 2001). The substantial role of dynamics in the trend turnaround has been supported also by results of other studies, e.g., Harris et al. (2008), Reinsel et al. (2005). There are various possible dynamical contributors to the long-term trend in total ozone, as discussed, e.g., by Staehelin et al. (2001) and Hudson et al. (2003).

The mid-1990s are important also for the lower stratospheric temperature trends at middle latitudes. While over the period 1979–2007 there is a negative trend ~0.5 K/decade in global temperature, no noticeable cooling is observed since 1995 (Randel et al., 2009). It may be caused by the change of trend in total ozone; since 1995 the positive trend in ozone (heating) rather compensates the trend caused by increasing greenhouse gas concentration (cooling), whereas in 1979–1994(5) the ozone trend impact on temperature supported the greenhouse gas-induced cooling (ozone was rather the main driver of cooling).

Since changes in dynamics seem to be rather decisive factor in turnaround of ozone trends at northern middle latitudes in the mid-1990s, we turn attention to ozone laminae, a parameter which is more sensitive to changes in dynamics than the total ozone or the ozone content in various atmospheric layers. Laminae are defined in Sect. 2. Figure 2 is based on large positive laminae. Such ozone laminae display a very strong seasonal variation, large majority of them occurring in January–May with peak in February-March. Long-term trends in ozone laminae are similar at latitudes of about 35–75° N, and for Europe, Northern America and Japan (Krizan and Lastovicka, 2005). Trends are robust in the sense that they depend little on the definition and method of determination of laminae, contrary to the overall ozone content in laminae or number of laminae themselves (Krizan and Lastovicka, 2005, 2006).

Figure 2 shows the long-term development of the overall ozone content in large laminae per ozone profile for several European stations. Since 1970 the overall ozone content was rapidly decreasing towards the mid-1990s (depression in 1993 can be attributed to the Mt. Pinatubo volcanic eruption, as volcanic aerosols peaked above Europe in spring 2003 after measurements of Ansman et al., 1997). The overall ozone content in laminae per profile was reduced to less than a half of its 1970 value. Then it turned to a rapid increase, in 2003 almost doubling its minimum level. In time this turnaround of trends coincides with the trend turnaround in the total columnar ozone, both in the mid-1990s. A similar change of trend was observed also at other northern middle and higher latitude ozonesonde stations (Krizan and Lastovicka, 2005).

The large positive laminae observed at analyzed European ozonesonde stations seem to be very predominantly formed at or near the edge of polar vortex as filaments. They are transported from the vortex boundary by vertically differential meridional wind. Balloon-borne measurements confirm well-resolved laminations near the vortex edge (Orsolini et al., 1998). When the vortex is more stable, weaker laminae are produced than in the case of unstable vortex, and conditions for their meridional transport are worse due to stronger zonal wind. Arctic stratospheric winters 1964/1965–1971/1972 were unusually warm (= less strong and stable vortex), followed by a period of "normal" winters and then by a period of very cold winters in the early and mid-1990s (Manney et al., 2005), which contributed to the negative trend in the overall ozone content in laminae. However, winters 1997/1998–2003/2004 were again unusually warm (Manney et al., 2005), which contributed to the observed positive trend in the overall ozone content in laminae. Thus the Arctic polar vortex behaviour as indicator of behaviour of dynamics coincides with trend in the overall ozone content in laminae and its turnaround in the mid-1990s. First results also indicate relation of this turnaround of trends in total ozone and laminae to the reversal of trend in the North Atlantic Oscillation (NAO) (Krizan and Lastovicka, 2006).

How is it with trends in the number of laminae per profile, i.e. in the lamina occurrence frequency? They display different trend behaviour and turnaround as discussed in Sect. 4.

4 MLT wind-like changes in trends

Routine wind measurements in the MLT region at heights of about 80–100 km have been carried out for several decades, particularly at several stations at northern higher middle latitudes. The most prominent components of the mid-latitude MLT winds are the prevailing (mean) winds and tidal winds, then planetary waves and gravity waves. Figure 3 shows how trends in the annual mean prevailing wind changed around 1990. Before 1990 both the annual prevailing zonal and meridional winds at Obninsk (55° N, 37° E) and Collm (52° N, 15° E) weakened, whereas after 1990 zonal wind strengthened and the negative trend in meridional wind levelled off. Shorter-period wind data series from Kazan (56° N, 49° E) and Saskatoon (52° N, 107° W) confirm this change of trend, (e.g., Jacobi et al., 2001), thus this change of trend in the MLT prevailing wind appears to be characteristic for the whole northern higher middle latitude belt. On the other hand Portnyagin et al. (2006) observed no increase of winter (December-February) mean zonal winds at Saskatoon (Canada) after 1985–1990 contrary to Collm. However, Jacobi et al. (2009) claim that this difference in Saskatoon wind behaviour is explainable by combined effect of different response to major stratospheric warming and the stratospheric warming distribution with time.

Diurnal and semidiurnal tides are the most important tidal modes; in the MLT region it is particularly the semidiurnal tide. The negative trend in semidiurnal tidal winds seems to cease after the mid 1980s or rather near 1990 (e.g., Jacobi et al., 1997; Portnyagin et al., 2006), or may even reverse. Observations at Scott Base, Antarctica reveal a positive trend since the late 1980s (Baumgaertner et al., 2005). Thus tides behave in a similar way as prevailing wind. Again a reversal of trend is observed near 1990, even though maybe a little earlier than in prevailing wind.

These trends correspond to heights of about 90–95 km. Let us now go up, to about 110 km. Wind data for trend studies are not available, but the worldwide ionosonde network provides long-time continuous measurements of foE, critical frequency of the ionospheric E region, which represents its maximum electron density located near 110 km. The overall long-term trend in foE is positive but weak (e.g., Bremer, 2008). It is mainly a consequence of greenhouse cooling-evoked changes in chemistry of minor constituents (e.g., Lastovicka et al., 2008). But how it looks in detail? Figure 4 shows the long-term development of foE for two high-quality data providing ionospheric stations in Europe located in the same latitudinal band as MLT wind stations used in Fig. 3, Slough/Chilton (51.6° N, 1.3° W) and Juliusruh (54.6° N, 13.4° E). Both stations reveal a weak negative trend before 1990 and slightly stronger positive trend after, which results in the overall slight positive trend of rather low significance. Thus we again observe tendency to turnaround of trends near 1990. It is necessary to mention that if we divide the data set used into two parts, 1975–1989 (negative trend) and 1990–2005 (positive trend), only the Slough trend for 1975–1989 is statistically significant at the 95% level. However, it is not surprising due to short data series (15 and 16 data points, respectively). On the other hand, at much higher heights, in foF1 near 200 km, such change of trends has not been observed at all.

Let us go from 90–95 km down into the mesosphere. As Fig. 5 shows, trends in prevailing zonal winds change their signs and below 83–85 km are opposite to those above, as found from partial reflection radar measurements at Juliusruh (54.6° N, 13.4° E) at heights of 68–93 km (Keuer et al., 2007). Moreover, trends in winter are opposite to those in summer. The annual mean trend is dominated by stronger summertime trends. Unfortunately, data on winds in the lower and middle mesosphere before 1990, suitable for long-term trend studies, are not available. Therefore possible turnaround of trends in mesospheric winds cannot be searched for.

The next step is to go down to the stratosphere. ERA-40 and similar datasets allow to study trends in winds in the middle and lower stratosphere. Here we present the results of the stratospheric wind data analysis based on ERA-40 wind data over 1957–2002. Wind data from 30° N northward in ERA-40 grid points are used but only the results for 52.5° N latitudinal circle are analyzed here, because they coincide best with latitudes of the MLT region wind observations used in the paper. Another paper will deal with results at other latitudes and also from other points of view, not only long-term trends. Most results will be presented for the 100 hPa level (heights ~15–16 km) and a few for the 10 hPa level (heights around 30 km) will be added. Heights around 100 hPa are the main contributor to ozone laminae, and the sudden stratospheric warming phenomenon is pronounced best at heights around 10 hPa, which are the reasons (together with data availability) why these two heights have been selected. Larger laminae occur most frequently at heights around 14 km according to Reid and Vaughan (1991), which is consistent with our result (Lastovicka, 2002) that more than 40% of the overall ozone content in large laminae is located between 100–200 hPa. Other authors (e.g., Pierce and Grant, 1998; Orsolini et al., 2001) put the maximum occurrence of laminae at potential temperatures of 375–400 K, i.e. again about 14–16 km.

Two parameters are studied, wind velocity and wind direction. Wind velocity trends change to some extent with longitude, therefore the wind velocity data are separated into four different sectors: Europe and western Siberia (0°–90° E), central and eastern Siberia and western Pacific Ocean (90°–190° E), eastern Pacific Ocean and Northern America (190°–300° E), and Atlantic Ocean (300°–360° E). On the other hand, wind direction does not change appreciably with longitude therefore only average data are shown. Only winter half of the year (October–March) results are presented hereafter.

When we began investigations, we expected stratospheric wind to follow the same trend pattern as ozone and, therefore, data were divided into three intervals according to the dates of change of trends in the northern midlatitude total ozone, i.e. before 1980 (little trend in ozone), 1980–1995 (rapid decrease of total ozone), 1995 onwards (increasing total ozone). Figure 6 (left columns – before 1980; middle columns – 1980–

1995; right columns – after 1995) shows that there is very little change, if any, in average wind directions with interval and this is the case also in individual sectors (not shown here). Winds are very predominantly westerlies (marked W) – for more than 90% of time wind blows in W, SW and NW sectors, i.e. with westerly (or eastward) zonal component. Meridional wind (N, S) occurs in 6–7 % of days, while winds with easterly zonal component are very rare.

Then we divided in a similar way wind velocities. Figure 7 presents distribution of occurrence frequency of individual wind velocities for Atlantic Ocean sector (300°–360° E) separately for the periods before 1980, 1980–1994, and the period since 1995. All four sectors provide similar pattern of change of wind velocity, but it is pronounced best in the Atlantic sector shown in Fig. 7. Slow winds dominate in the period before 1980. In the period of ozone recovery after 1995 there is a tendency to dominance in medium-speed winds. High-speed winds occur most often in the period of decreasing ozone content (1980–1994) (middle column). The difference between periods before 1980 and 1980–1994 is not small, for example velocity of 40 m s^{-1} occurs twice as much for the latter period (Fig. 7).

However, such result may be caused by two different effects. Either wind is stronger in the middle period, because this period is the period of decreasing ozone concentration, or the trend turnaround point is near the centre of the middle period (as is the trend turnaround point for MLT region winds) with positive trend before and negative trend after the turnaround point. To resolve this question, Fig. 8 reveals time development of average wintertime wind velocities over the entire analyzed period. No change of trend is indicated near the years 1980 and 1995; the change of trend is indicated near 1990 or slightly before. That means that the trend in the 100 hPa wind velocity changes not as trends in total ozone, it changes in the same time as the MLT region wind trends. Figure 9 presents the stratospheric wind data over the same period as MLT wind data in Fig. 3. Even though large year-to-year variability does not allow determine precisely the turnaround year of trends, it is quite evident that the turnaround occurred not in the years of turnarounds of trends in total ozone. It occurred near 1990 in the years of turnaround of trends in the MLT winds shown in Fig. 3. We assume turnaround year to be 1990 and divide data into two data sets as shown in Fig. 9, 1973–1990 and 1991–2002. Then the positive trend in the former interval is statistically insignificant at the 95% level due to very large oscillations of winds between years 1985–1990, whereas the negative trend in the latter interval is statistically significant at the 95% level. However, small number of data points allows question sense/reliability of statistical significance estimates.

The above stratospheric wind velocity analyses have been made for the sector 300–360° E, while MLT wind measurements and ozone laminae observations are from the sector 0–90° E, even though except for Obninsk from the sub-sector 0–20° E, i.e. near the border between these two sectors. Therefore Fig. 10 shows the same as Fig. 9 but for the sector 0–90° E. In this sector the trends are much weaker and insignificant but of the same sign as in the sector 300–360° E. It is necessary to mention that out of the four sectors the trends and change of trends near 1990 are pronounced best in the sector 300–360° E and worst in the sector 0–90° E. Trends in 100 hPa winds are less pronounced than in the MLT winds (Fig. 3) or in the number of laminae (Fig. 12) but reveal the same turnaround of trends near 1990.

The 10 hPa wind pattern is shown in Fig. 11 together with the 100 hPa wind pattern for the sector 300–360° E. Winds at 10 hPa are stronger as expected. They strengthen since 1957 until the late 1980s in a similar way as winds at 100 hPa and year-to-year variations and extreme wind appearance at 10 hPa is mostly supported by similar behaviour at 100 hPa. However, very extremes after 1990 in the years 1996 and 1997 (positive), and 2002 (negative) are not supported by 100 hPa behaviour at all. They look like outliers with possibility to be caused by data problems. With these data two interpretations of trend changes are possible – increase before 1990 and decrease after 1990, as indicated by trend lines in Fig. 11, or increase until 1980, then stagnation until 1997, and then decrease of wind velocity in a way more similar to ozone-like behaviour of trends. Therefore we cannot conclude what is the behaviour of trends in wind velocity at 10 hPa. Reliability of some extremes in data needs to be checked. On the other hand, at 100 hPa both negative and positive trends are statistically significant at the 95% level due to the longer data series used compared to Fig. 9, where only the positive trend is statistically significant at the 95% level.

All the above analyses of stratospheric wind trends were made for 52.5° N (50° N provides the same pattern), i.e. for higher middle latitudes. Now we turn attention to other latitudes and to 100 hPa, where trends are stronger and better pronounced and their changes more evident. Behaviour of stratospheric winds at other latitudes and general analysis (not only trend analysis) of wind behaviour is topic of another paper. Therefore we shall only briefly mention results for the Atlantic sector (300°–360° E) and from the point of view of trends. The trend pattern at 62.5° N is quite similar and at 72.5° N is also fairly similar to that at 52.5° N. Towards lower latitudes, at 42.5° N the pattern is less similar, and at 32.5° N it is different. It is necessary to mention that at 32.5° N, the 100 hPa wind velocity is to some extent influenced by the subtropical tropopause jet, so its different behaviour is not surprising.

Another quantity, which responds to dynamical processes, is ozone laminae (e.g., Krizan and Lastovicka, 2006). As it is clearly seen from Fig. 12, occurrence frequency of both large and small laminae substantially and quite significantly decreased since 1970 to 1989. This decrease was by a factor of 3 for large laminae and by a factor of 1.5 for small laminae. Then the number of laminae turned to increase, which compensated for half of previous reduction for large laminae, but even overcompensated previous decrease for small laminae. However, it is necessary to mention that in the early 1990s most sounding stations changed ozonesondes to EES sondes with higher vertical resolution, which increased detection of narrower small laminae but little affected detection of broader large laminae. This explains much larger difference between small and large laminae in the 1990s compared to the 1980s. We cannot exclude that such an effect shifted minimum of small laminae slightly towards the 1980s but this minimum occurred anyway well before 1995. The turnaround year 1989 is within accuracy of determination identical with year 1990, the turnaround year of MLT region winds (Fig. 3), not like total ozone and the overall ozone amount in laminae per profile with trend turnaround in the mid-1990s (Sect. 3). It is necessary to mention that data including year-to-year variability of various origins allow estimate the turnaround year not better than ±1 year at best. On the other hand, an accurate determination of the year of turnaround is unnecessary for the purpose of the paper, we need only to know if the turnaround year is close to 1990 or rather 1995. A smoothed behaviour of large laminae provides turnaround of trend slightly later, in the early 1990s, but again close to 1990, not to 1995. For other regions (Canada, northern Japan) and large laminae, the turnaround point occurs later, in the mid-1990s like in total ozone (Krizan and Lastovicka, 2005, their Fig. 11). Thus in the number of large laminae (not small laminae), the pattern in the European sector versus Japan and Canada is different and, therefore, we will take them in further considerations with care.

To be able to interpret the partly different behaviour of large and small laminae, height distribution of laminae is presented in Fig. 13, which reveals substantial differences in height distribution of large and small laminae. Almost all large laminae are located in two height regions, tropopause – tropopause+5km and tropopause + 5 km – tropopause+10km, i.e. in the first 10 km above the tropopause. Distribution of small laminae is much broader, with a broad, flat peak in the first 15 km above the tropopause and a significant tropospheric contribution, i.e. they occur more or less in the whole height range 0–30 km. This creates conditions for their different behaviour as observed, and indicates rather different origin of large and small laminae. Small laminae are probably formed by several mechanisms including important role of upward propagating gravity waves.

5 Discussion

Long-term trends in the middle atmosphere dynamics-related quantities appear to group into two different clusters according to years of trend turnaround and related mechanisms responsible for change of trends. One group displays the total ozone trend-like behaviour, the other group the MLT wind trend-like behaviour.

As concerns the ozone-like trend pattern, it is observed in the total ozone and in the overall ozone content in laminae per profile. As already discussed in Sect. 3, the Arctic polar vortex behaviour as indicator of behaviour of dynamics, coincides with trend in the overall ozone content in laminae and its turnaround in the mid-1990s. First results also indicate some relation of this turnaround of trends in total ozone and laminae to reversal of trend in the North Atlantic Oscillation (NAO). This means that a substantial role in driving trend changes might be played by phenomena of tropospheric origin; the NAO is tropospheric phenomenon, and trigger of changes in the stratospheric polar vortex, particularly of sudden stratospheric warming, is the planetary wave activity of tropospheric origin. Further investigations of the role of tropospheric phenomena are needed.

The other group behaves like MLT winds. It consists of winds in the mesopause region (90–95 km), maximum electron density in the E region (~110 km), winds at 100 hPa, and number of small ozone laminae. Trends in winds in the mesopause region and at 100 hPa have opposite direction, but it is not surprising as trends change their sign in 80–85 km (Fig. 5). The changes of trends observed around 1990 are very probably caused not directly by the increasing greenhouse concentration; e.g. they are not observed in trends in mesospheric temperatures (Beig et al., 2003) or trends in the height of maximum of the E region, hmE (Lastovicka et al., 2008), which both are caused by increasing concentration of greenhouse gases. These changes of trends are probably of rather unclear dynamical origin. One possibility are long-term changes in the gravity wave source activity (predominantly in the troposphere) and gravity wave penetration to the MLT region heights, because winds are sensitive to gravity wave forcing (particularly near the mesopause). The E-region ionosphere also responds to changes in the gravity wave activity, and gravity waves contribute significantly to production of small laminae (e.g., Reid et al., 1994; Pierce and Grant, 1998). However, observational information on trends in the gravity wave activity in the MLT region is very scarce, essentially missing (Lastovicka et al., 2008). As the main source of gravity wave activity is the troposphere, these trends may also be affected by the tropospheric dynamics but by its other features than the ozone-like trends. It is necessary to mention that changes of stratospheric (and mesospheric) filtering of gravity waves may also play a role in changes of trends. To check the hypothesis on the role of gravity waves, more data and information about long-term behaviour of gravity wave activity at various heights (it might be height-dependent) is required.

Jacobi et al. (2009) derived from the NCEP/NCAR reanalyses the amplitudes of the stratospheric stationary planetary waves of zonal wavenumber 1 (SPW1) for 50° N and 100, 30 and 10 hPa. The SPW1 amplitudes slightly decrease in 1973–1990 but increase in 1991–2002 (Jacobi et al., 2009, their Fig. 7). In other words, they display the MLT wind-like type of change of trend. Moreover, European MLT region wind variations reveal similarity with the 100 hPa SPW1 variations before the early 1990s, whereas in more recent years they are more strongly connected with the 30 hPa or 10 hPa SPW1 variations (Jacobi et al., 2009).

The above turnarounds of trends concern dynamics of the middle atmosphere. Dates of changing/reversing trends in temperature-related parameters are different, if such reversals exist at all, because trends in the mesospheric temperatures (e.g., Beig et al., 2003) do not reverse. Trends in the lower stratospheric temperature seem to cease after 1995 (Randel et al., 2009), but this change of trend is not of direct dynamical origin, it is caused by reversal of trend in ozone concentration. Trends in the annual amplitude of temperature in the mesosphere over midlatitude Europe reversed in ~2002 (Offermann et al., 2006). Trends in summer duration in the stratosphere and mesosphere at latitudes northward of ~50° N reversed in ~1980 (Offermann et al., 2005). However, as far as we know, no remarkable change in trends in mesospheric temperature-related parameters has been reported to occur near 1990 or 1995.

It is important to mention that changes in the tropospheric dynamics seem to play a role in the above discussed changes of trends in the middle atmosphere dynamics, i.e. that in situ sources may not be the primary drivers of these changes of trends. This is probably the reason why these changes are not consistent with the upper atmosphere trend scenario described by Lastovicka et al. (2006, 2008).

6 Conclusions

The main aim of the paper is to answer the question if long-term changes in the middle atmosphere (mesosphere and stratosphere) dynamics form one single regime of change, or if the dynamics in the upper and lower parts of the middle atmosphere display long-term changes governed by two different regimes and different drivers. We find two different regimes but these are not divided by an altitude, they are distinguished by different turnaround year of trends and by different drivers of the turnaround of trends.

Observational results show "clustering" of dates of reversal of trends into two basic groups, near 1990 and near 1995 (or mid-1990s), which means that two different regimes (and related different drivers) are present in changes of trends in the dynamics of the middle atmosphere. The results, which form the observational "scenario" of change of trends in the dynamics in the middle atmosphere in or around the 1990s, may be summarized as follows:

1. Zonal as well as meridional prevailing and semidiurnal tidal winds in the mesopause/MLT region (heights ∼90–95 km) at northern higher middle latitudes display a reversal or levelling off of trends around 1990. A similar turnaround point in trends, ∼1990, is observed in the European sector at the same latitudes in the E-region ionosphere in foE (heights ∼110 km), in number of small ozone laminae (troposphere to middle stratosphere), and little bit later in number of large ozone laminae (lower stratosphere) in the European sector (not in American and Japan sector). Winds in the lower stratosphere at 52.5° N change trends also near 1990. Similar change of trends has been reported also for the stratospheric SPW1 at 50° N. These changes of trends are probably of rather unclear dynamical origin. One possibility is long-term changes in the gravity wave source activity (mostly of tropospheric origin) and gravity wave penetration upwards up to the MLT region.

2. At northern middle latitudes the total columnar ozone and the overall ozone content in large laminae per profile reversed trends in the mid-1990, near 1995. The reversal of trend in total ozone results in ceasing of trends in the lower stratospheric

temperature after 1995 as a consequence of oppositely acting increase of the greenhouse gas concentration (cooling) and increase of ozone (warming). The Arctic polar vortex behaviour as indicator of behaviour of dynamics coincides with trend in the overall ozone content in laminae per profile and its turnaround in the mid-1990s. First results also indicate relation of this turnaround of trends in total ozone and laminae overall ozone content to reversal of trend in the North Atlantic Oscillation (NAO).

The above results form a "skeleton" of scenario of change of trends in the dynamics of the middle atmosphere in the 1990s. This "skeleton" needs to be completed by other results.

It is interesting that both groups reveal some role of tropospheric phenomena or phenomena of tropospheric origin in their trend reversals.

Our results are based partly on latitudinal circle data, partly on the European sector data only. Some data display the same trend behaviour in various longitudinal regions (e.g., the overall ozone content in laminae per profile) but at least the mesopause region winds (e.g., Jacobi et al., 2009) display different trend behaviour in the North America versus Europe (Saskatoon – Collm and Obninsk) and the number of large laminae displays different trend change dating in Europe versus the Northern America and Japan, therefore our results are valid for European sector and in other sectors might be partly different (topic of future studies).

Here we discuss stratospheric winds only from the point of view of long-term trend behaviour. Analysis of other features of their behaviour is topic of MSc thesis and another paper in preparation.

Data which we use here cover the upper part of the middle atmosphere above 90 km and the lower part of the middle atmosphere below 10 hPa (~30 km). In the lower and middle mesosphere the data suitable for wind trend studies are missing. The ERA-40 data go up to 1 hPa, so in future we will analyze the ERA-40 and/or new ERA-Interim wind data at higher altitudes, taking however into account their possible reliability problems near upper boundary. Wind data suitable for trend studies down to about 80–75 km appeared only during the 1990s, but we hope that careful checking of some older data allow go somewhat more backward to check trend changeover existence and dating. These future observational studies will be accompanied by model simulations with LIM model of the University of Leipzig in collaboration in a joint DFG-GACR project like in Jacobi et al. (2009).

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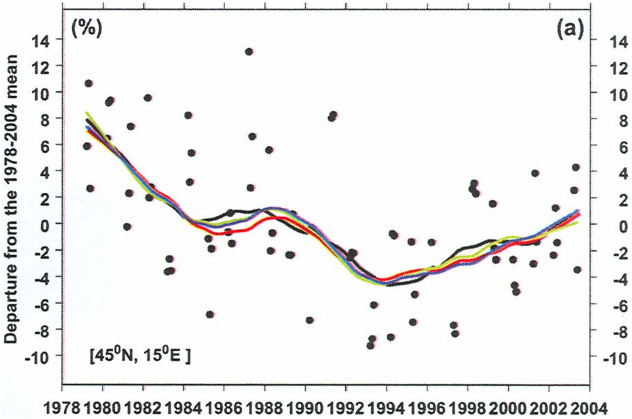

Fig. 1. Modelled and observed monthly mean values of total ozone in the spring seasons of 1979–2003 for grid point 45° N, 15° E. Black dots and curve – observed and smoothed data; red curve – smoothed data, flexible trend; blue curve – double linear trend; green curve – smoothed data, chlorine trend. Adapted from Krzyscin et al. (2006).

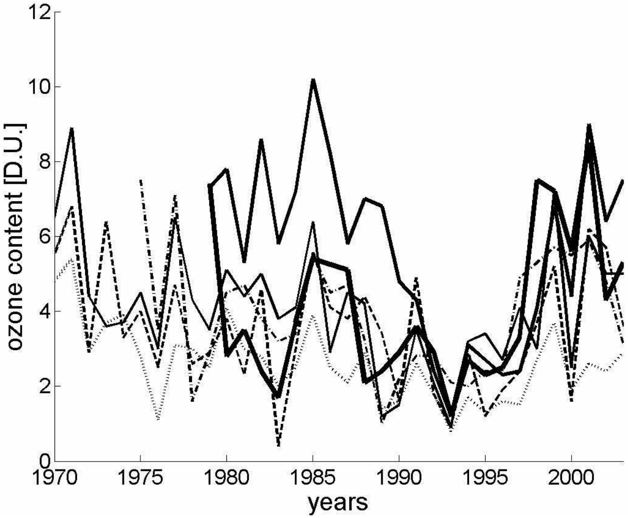

Fig. 2. The overall ozone content in large positive laminae per profile for the European middle latitude stations Hohenpeissenberg (dotted line), Legionowo (heavy full line), Lindenberg (dashed-dotted line), Praha-Libus (medium full line), Payerne (thin full line) and Uccle (dashed line), 1970–2003. After Krizan and Lastovicka (2005).

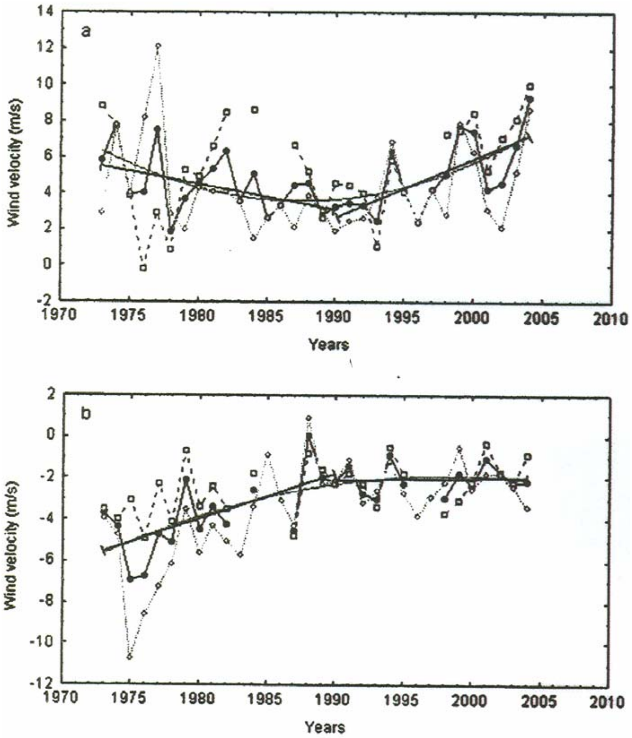

Fig. 3. MLT annual mean prevailing winds over Obninsk (55° N, 37° E) and Collm (52° N, 15° E), empty squares (dashed line) – Obninsk, empty cubes (dotted line) – Collm, full cubes (full line) – mean values; trend lines are included; **(a)** top panel – zonal component, **(b)** bottom panel – meridional component (Lastovicka et al., 2008).

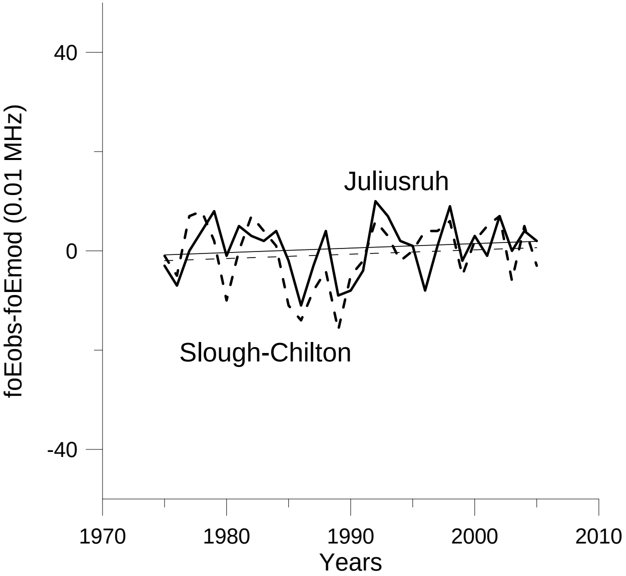

Fig. 4. Change of trend in 1990 for ΔfoE = $\mathrm{foE_{obs}}$–$\mathrm{foE_{mod}}$ (empirical model provides best fit values for the given level of solar and geomagnetic activity) for two high-quality European stations Slough/Chilton (dashed line) and Juliusruh (solid line). Data for period 1975–2005. Straight lines – linear fit.

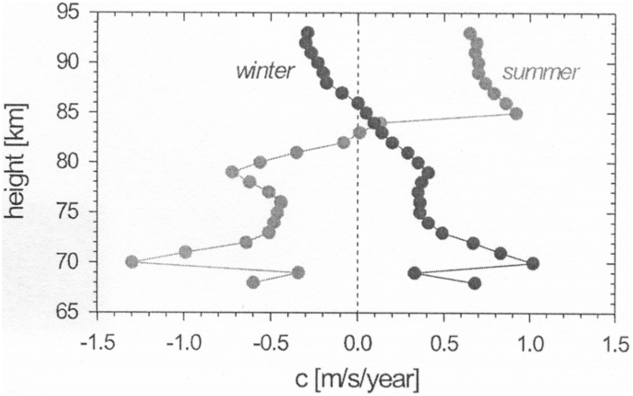

Fig. 5. Trend of the MLT zonal wind at Juliusruh (54.6° N, 13.4° E) as a function of height separately for summer and winter, 1990–2005 (Keuer et al., 2007).

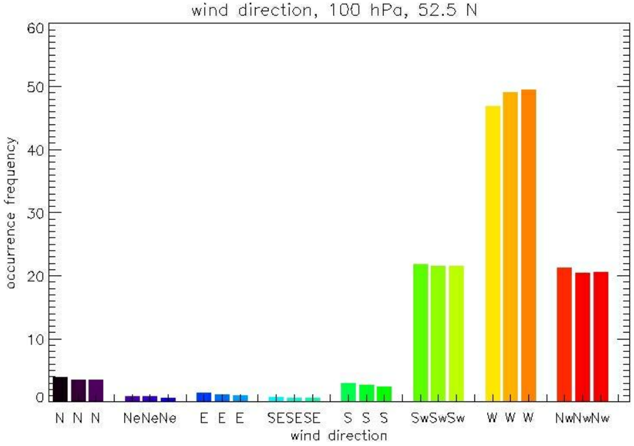

Fig. 6. Distribution of occurrence frequency (in percentage of all cases) of wind directions at 100 hPa, 52.5° N, winter. For the given wind direction the left column represents period 1960–1979 (relatively stable total ozone level), the middle column represents period 1980–1994 (significant decrease of ozone concentration), and the right column represents period 1995–2002 (some increase of ozone concentration). W – wind from the west (westerly wind, eastward), etc.

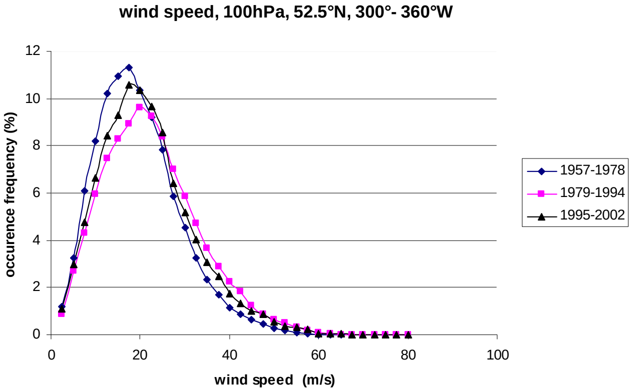

Fig. 7. Distribution of occurrence frequency (in percentage of all cases) of wind velocities at 100 hPa for sector 300°–360° E, 52.5° N, winter. Blue curve – 1957–1978; magenta curve – 1979–1994; black curve – 1995–2002.

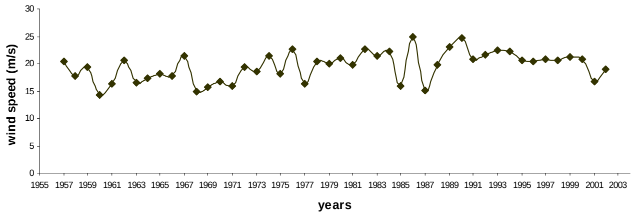

Fig. 8. Time development of the winter (October–March) average wind speed, 100 hPa, sector 300°–360° E, 52.5° N, 1957–2002.

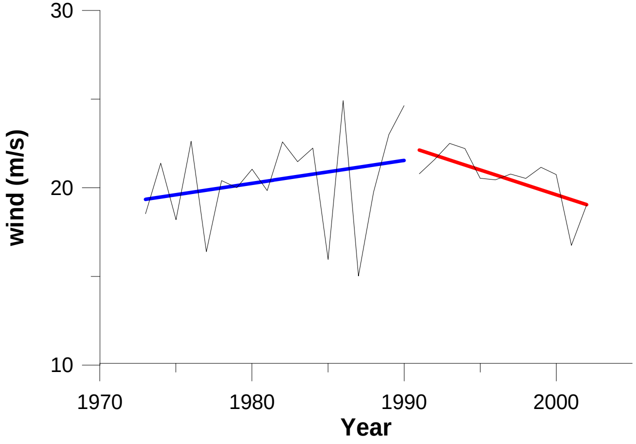

Fig. 9. Time development of the winter (October-March) average wind speed, 100 hPa, sector 300°–360° E, 52.5° N, 1973–2002; wind trend – blue 1973–1990, red 1991–2002.

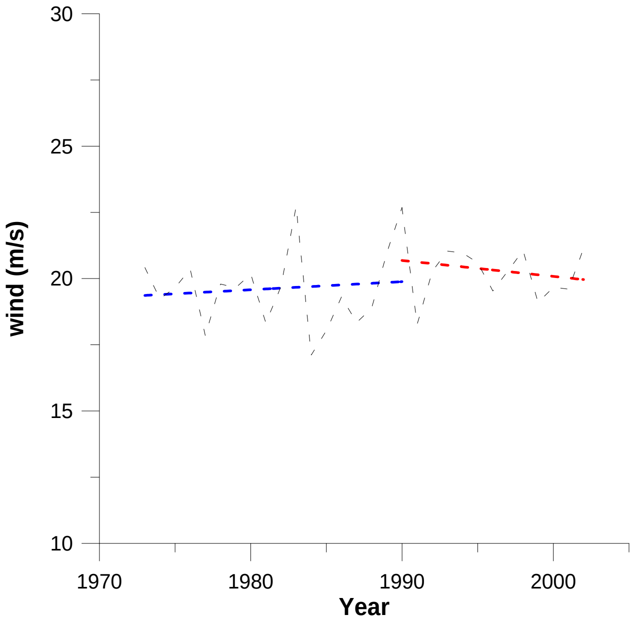

Fig. 10. Time development of the winter (October-March) average wind speed, 100 hPa, sector 0°–90° E, 52.5° N, 1973–2002; wind trend – blue 1973–1990, red 1990–2002.

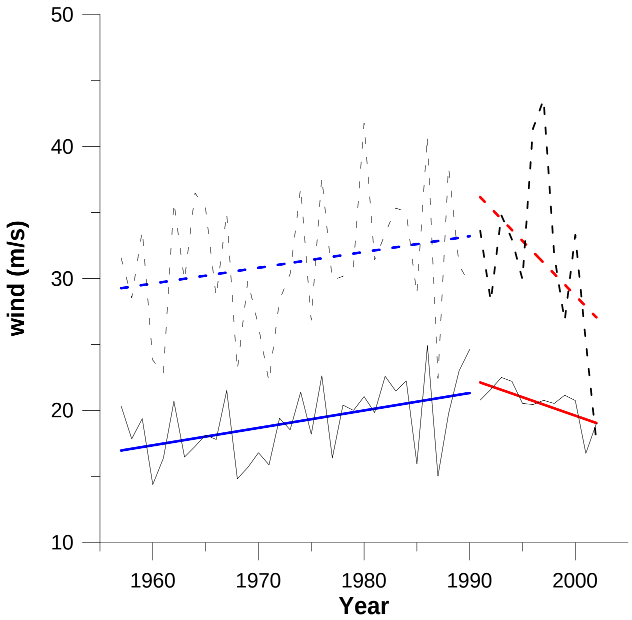

Fig. 11. Time development of the winter (October–March) average wind speed, 100 hPa (full curves – bottom) and 10 hPa (dashed curves – top), sector 300°–360° E, 52.5° N, 1957–2002; wind trend – blue 1957–1990, red 1991–2002.

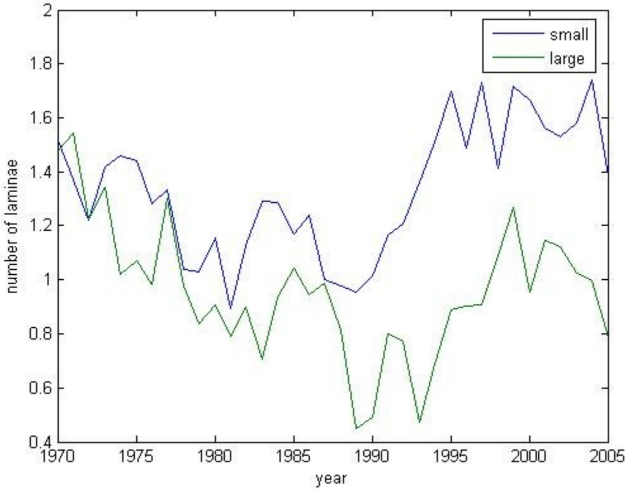

Fig. 12. Trends in the number of laminae per profile for large (>40 nbar) and small (10–20 nbar) positive laminae over Europe, middle latitudes (average from Payerne, Hohenpeissenberg and Uccle), data only for "lamina season" January–May 1970–2003.

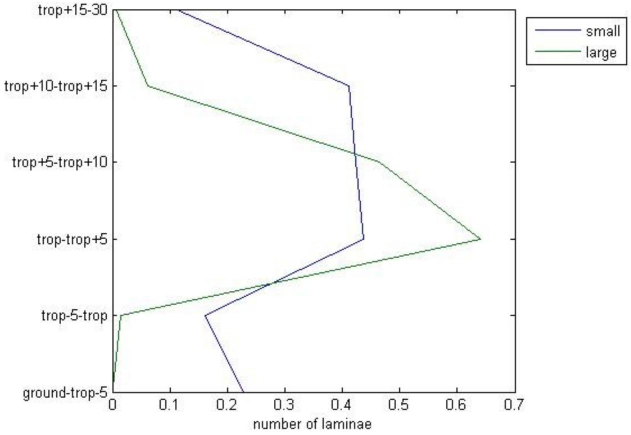

Fig. 13. Height distribution of the number of laminae per profile for large (>40 nbar) and small (10–20 nbar) positive laminae over Europe, middle latitudes, data only for "lamina season" January–May. Data points correspond to layers (from bottom up): surface – tropopause-5 km; tropopause-5 km – tropopause; tropopause – tropopause + 5 km; tropopause + 5 km – tropopause + 10 km; tropopause + 10 km – tropopause + 15 km; above tropopause+15km (sondes usually burst around 30 km).