Assessing the role of planetary and gravity waves on the vertical structure of ozone over midlatitudinal Europe

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Abstract

Planetary and gravity waves play an important role in the dynamics of the atmosphere. They are present in the atmospheric distribution of temperature, wind and ozone content. These waves are detectable also in the vertical profile of ozone and they cause its undulation. One of the structures occurring in the vertical ozone profile is laminae, which are narrow layers of enhanced or depleted ozone concentration in the vertical ozone profile. They are connected with the total amount of ozone in the atmosphere and with the activity of the planetary and the gravity waves. The aim of this paper is quantifying these processes in the central Europe. We compare the occurrence of laminae induced by planetary waves (PL) with the occurrence of these induced by gravity waves (GL). We show that the PL are 3-5 times more frequent than the gravity wave ones.   There is a strong annual variation of PL, while GL exhibit only a very weak variation. With the increasing lamina size the share of GL decreases and the share of PL increases. The vertical profile of lamina occurrence is different for small planetary wave and gravity wave laminae. The trend of large lamina occurrence frequency is given by the trend in PL, not by GL.

Key words: ozone lamina; vertical ozone profile, planetary wave activity, gravity waves

1. Introduction

There are various structures in the vertical profile of ozone affected by the activity of the planetary and gravity waves. Ones of them are narrow layers of the enhanced or depleted ozone concentration in the ozone vertical profile, which are called ozone laminae. The first investigation of these structures was made by Dobson (1973), who found that they occur predominantly in a cold half of the year. The existence of laminae was confirmed by lidar and satellite measurements (Bird et al., 1997, Orsolini et al., 1997, Kar et al., 2002). They were found also in water vapour in the stratosphere (Teitelbaum et al., 2000). The dynamics of the stratosphere plays a crucial role in a lamina formation. This finding was confirmed by the ability of dynamical models to capture these narrow layers (Manney et al., 2000, Orsolini et al., 2001). The number of large laminae is strongly correlated with the total ozone content and it is the reason why we have been interested in laminae (Krizan and Lastovicka, 2005).

The laminae are not only the indicator of the atmospheric ozone content but also they are connected with the gravity and planetary wave activity. Teitelbaum et al. (1995) developed a identification procedure which enable us to detect the planetary and gravity wave activity in the ozone vertical profile. In this paper we apply this method to ozone laminae and each lamina we sort to the one of the following groups: laminae induced by gravity wave activity (GL), by planetary wave activity (PL) and laminae which are neither induced by the gravity waves nor by the planetary waves. Similar method was used by Grant et al., (1998) and Pierce and Grant (1998) but only for the Wallops Island station. The aim of this paper is finding the characteristics of GL and PL in central Europe in the period 1970-2016. At first we test if the Teitelbaum method is suitable for central Europe. Next the annual variation of GL and PL is examined. Then we explore the dependence of lamina composition on their size. We also compare the vertical distribution of GL and PL. We deal with their trends. The content of this paper is as follows: section 2 describes methods and data, section 3 gives results, in section 4 the results are discussed and the last section is conclusions.

2. Methods and data

Now we shortly describe the lamina searching procedure. Each positive lamina consists of the three main points: the lower minimum, the main maximum and the upper minimum. The depth of lamina must be between 500 and 3500 m due to the vertical resolution of the ozonosondes (lower limit) and due to the fact that the ozone lamina is a narrow layer of the enhanced ozone concentration (upper limit). The size of laminae is given as a difference between the ozone concentration in the main maximum and the average concentration from both minima. More about the lamina searching procedure can be found in (Krizan and Lastovicka, 2004) and (Lastovicka and Krizan, 2005).

The method used in this paper for the searching the activity of gravity and planetary waves in the ozone profile is a modification of the methods given by Teitelbaum et al. (1995). Figure 1 (upper panel) shows the real ozone profile at Hohenpeissenberg on February 2, 1970. We use the linear interpolation with the step 50 m for approximating the ozone profile with the high vertical resolution. Then the 50 point moving average (2500 m in vertical) is applied to this real profile to obtain the smooth profile. This smooth profile is also displayed in fig.1 (upper panel). The same procedure is applied to the potential temperature and the results are given in fig. 1 (lower panel). In the next step we compute the differences between the high resolution profile and the smooth profile for the ozone partial pressure (fig 2 upper panel) and the potential temperature (fig 2 lower panel). The differences are much higher for the ozone profile than for the potential temperature profile. The differences in the vertical gradients of the ozone partial pressure and the potential temperature must be taken into account. So we must apply the following correction factor to the potential temperature perturbations:

$$R(z) = [(1/O_{3avg})*(dO_3/dz)]*[(1/\Theta_{avg})*(d\Theta/dz)] \qquad (1, 1)$$

where O_{3avg} (Θ_{avg}) is the average ozone partial pressure (potential temperature) profile in the layer with the width dz. The vertical distribution of this correction is given in fig.3 (upper panel). The correction is the highest in the lower stratosphere where the vertical gradient of ozone is strong. Above 20 km we observe the negative values of this factor, which is predominantly given by the negative gradient of the ozone partial pressure and the strong positive gradient of the potential temperature. When we multiply the potential temperature perturbations with this correction, we obtain the perturbations, which are shown in fig. 3 (lower panel). These new perturbations are not similar to that given in fig.2 –lower panel. In each point of the high resolution ozone profile we compute the correlation coefficient between the ozone perturbations and the scaled potential temperature perturbation up to 5 km above this point. The vertical dependence of this correlation coefficient from the ground to the point which is situated 5km below the highest ozone profile point is seen in fig.4. If the correlation coefficient is greater than 0.7, the vertical ozone profile in this point is influenced by the gravity waves. In fig 4 the correlations are higher than 0.7 at some altitudes above 5 km and below 15 km. If the lamina maximum is situated in this high correlation area, we conclude this lamina is induced by the gravity waves. On the other hand, if these correlations are low (between -0.3 and 0.3), we consider the ozone profile to be influenced by the planetary waves in this point (from 17 to 22 km on fig. 4) and again if there is a lamina maximum there we consider this lamina as the one induced by the planetary waves. When the correlation coefficient is above 0.3 and below 0.7 or below -0.3 we are not able to evaluate what type of laminae is present and call them indistinguishable laminae. The boundary values of correlation coefficients were taken from Teitelbaum et al. (1995)

We are going to apply this procedure to the following European midlatitudes stations: Hohenpeissenberg (Germany, 1970-2016, 5166 files), Payerne (Switzerland, 1970-2016, 5998 files), Uccle (Belgium, 1970-2015, 6221 files), Lindenberg (Germany, 1975-2013, 2380 files) and Legionowo (Poland, 1979-2016, 1728 files). These data were taken from WOUDC Toronto (http://woudc.org/archive/Archive-NewFormat/). During the research some problems with a vertical resolution of ozone profile were occurred and so at the end we exclude the data from the station Lindenberg. The Hohenpeissenberg data was used only for large laminae.

3. Results

3.1. Performance of method

At first we must answer the question if the procedure used in the paper is successful in partitioning of laminae to the groups. If the procedure is suitable, the number of the indistinguishable laminae cannot be very high. The performance of this procedure is given in tab.1 for Hohenpeissenberg for each month and for all laminae regardless the size. The results at the other stations are very similar. From this table we see that approximately 47 % of all laminae are PL, while GL laminae formed about 10 % and the share of indistinguishable laminae is about 43 %. It means more than 50 % of all laminae can be divided into the laminae induced by the gravity or the planetary wave activity. So we can conclude this procedure is successful in lamina partitioning, because nobody can expect only GL and PL will be present and no indistinguishable laminae. Practically there is no yearly course in the lamina composition.

3.2. Vertical resolution and number of laminae

At first we must look at the homogeneity of the sonde vertical resolution used in this paper. The results are given in fig. 5. We see the resolution is not homogenous and the resolution increases (vertical distance decreases) in the period 1970-2016. And thus we must ask the question if this resolution change has effect on a number of laminae detected in the profile. We have computed correlation coefficient between the yearly values of lamina number and vertical resolution. If these correlations are significant the resolution influences the lamina number and vice versa. We did the correlations for the following groups of laminae: small (<1 mPa), medium (1-4 mPa) and large (>4 mPa). The results are shown in tab.1. The number of small laminae is strongly correlated with vertical resolution. It means the numbers of small laminae are affected by the resolution. With increasing size of laminae these correlations decrease. For large laminae the results are station dependant. These results are a bit surprising because one expects negative correlations of lamina number with resolution and these negative correlations were observed only for small laminae. For the explanation of these results we must look at the average lamina depth in small, medium, and large laminae (table 2), which was obtained for the best vertical resolution (below 100 m). We can see the increase of lamina depth with increasing size. When the depth of laminae is small (small laminae), the vertical resolution strongly influences the lamina number, because with decreasing resolution the number of detected laminae decreases. On the other hand, the average depth of large laminae is above the worst vertical resolution (800 m- fig.5) and so the increasing resolution does not influence significantly the number of detected laminae.

According to the resolution results we can select periods used in this paper because we are interested also in small and medium laminae number of which is resolution dependant. To exclude this dependence, the vertical resolution of sonde must be comparable or smaller than the average depth of laminae and thus one can see (table 2) the maximal vertical resolution in the case of small laminae must be 100 m and for medium laminae 500 m. The depth of large laminae is above the worst vertical resolution so the large lamina results are not resolution dependant. Originally we considered also the station Lindenberg but it had to be excluded due to large and variable vertical resolution. The station Hohenpeissenberg is suitable only for several years after 2010. Only the stations Payerne and Uccle have suitable vertical resolution in the period 1990-2016 and the station Legionowo in the period 1995-2016. Because we must do compromise between the quality and amount of data we take into account only these three stations in the period 1995- 2016 for the small and medium laminae and the Hoheinpeissenberg data for the large ones.

3.3. Annual variation of laminae induced by the gravity and the planetary wave activity

Figure 6 shows the annual variation of the number of laminae larger than 2 mPa for GL and PL at all stations used in this paper. The group of lines with the strong annual variation with maximum in winter and minimum in summer/autumn are PL while the lines with the only very weak variation belong to GL. This different behaviour of the annual variation is the evidence that the both type of laminae are formed by different processes.

3.3. Dependence of lamina type on the size of laminae

In this section we deal with the lamina type occurrence frequency in the selected classes of lamina size. The laminae were sorted to the following groups: small (<1 mPa), medium size (1-4 mPa) and large (>4 mPa) and in each group we found the occurrence frequency of different types of laminae. The results are presented in fig.7. The results are almost identical for all stations. The share of GL is decreasing with the increasing size and the opposite is true for PL. The performance of used procedure increases with the increasing lamina size (the share of indistinguishable laminae decreases). The gravity waves are able to produce predominantly small laminae, while the planetary waves produce also the large ones. Similar results were also obtained by Teitelbaum et al. (1995).

3.4. Vertical dependence of the occurrence of advection and gravity wave laminae

Now we examine the altitudinal dependence of occurrence of GL and PL at the stations used in this paper for all seasons. March, April and May form spring, June, July, August are summer months, September, October and November are the autumn ones and December, January and February is winter. We divided the ozone vertical profile into 2 km wide intervals and in each interval we search for the lamina occurrence. The results are displayed as the percentage of all laminae which occur in the individual altitude interval. We grouped laminae into two groups: small (<2 mPa) and large (>2 mPa) and in each group we are searching for the lamina occurrence. The results are displayed only for the station Uccle, because at the other stations the results are similar. The winter results are given in fig. 8 for the large (upper panel) and the small (lower panel) laminae. The large laminae have similar behaviour both for GL and PL. Their maximal occurrence is observed in the lower stratosphere and there are no large laminae in the troposphere. On the other hand, the occurrence of the small laminae is different. GL have maximal occurrence in the troposphere where the occurrence of PL is small. Small PL have the maximal occurrence in the lower stratosphere, where the small gravity wave laminae are rare. In the troposphere there is local minimum in small PL and the main maximum in the small gravity wave occurrence. Spring (fig.9) behaviour of the lamina occurrence is similar to the winter one. In summer (fig.10) the large GL have broad stratospheric maximum and the smaller maximum is observed in the troposphere. Large GL have sharper stratospheric maximum and they are very little present in the troposphere. Small PL maximum is observed in the stratosphere, while the small GL have tropospheric maximum. At the nearly same height we observe local minimum in small GL and maximum in the gravity wave ones. In autumn (fig.11) the behaviour of large laminae is a bit similar to the summer one and the main maximum in occurrence of small PL is higher than that of the laminae induced by the planetary wave.

3.5 Trend of the large laminae

Now the long-term of the large laminae occurrence (larger than 4 mPa) is investigated. The results are shown in fig. 12. A change in the trend of the PL in the mid-1990s is seen. Before the mid-1990s the negative trend is observed, while after this point the positive one is present. This fact confirms the findings of Krizan and Lastovicka (2006). But this is not the main massage of this paper. The main massage of this paper concerning the trend is the following: we observe a huge difference in the long- term trend between GL and PL: trend of PL has the sharp change in the mid-1990s, which is confirmed by significant negative trend of the lamina number before 1995 and the significant change of this trend in 1995 (tab.4), while GL has a bit smaller insignificant negative trend before 1995 and insignificant trend change in 1995. So in the case of PL we observe change in trend in 1995, but in the case of GL no change occurred. The piecewise regression model is suitable only for PL. On the other hand, the most proper model for GL is the standard regression for the period 1970-2016. In this case we obtain significant negative trend of lamina number about 17 % / decade.

4. Discussion

We found the occurrence frequency of PL to be about 4-6 times larger than that of GL. The most frequent way of formation of the laminae induced by planetary waves is vertically different advection of air with the various ozone content (Manney et al., 2000). Tomikawa et al. (2002) proposed as one of lamina formation mechanism vertical shear of the subtropical jet. In these processes we observe transformation of the horizontal gradient of the ozone concentration into the vertical one. The air with the high ozone concentration comes to the central Europe in winter from the edge of the polar vortex (Orsolini et al., 2001). On the other hand, the low ozone air has its origin inside the polar vortex and it is transported to the mid latitudes (Reid and Vaughan, 1991) or it is the air from the low latitudes where ozone concentration is low (Orsolini et al., 1995).

The strong source of gravity waves is orography (Smith et al., 2008), especially passing the air through a mountain range when the gravity waves occur in the downwind side of the ridge. For stations used in this paper the most important mountains are the Alps. These stations are situated in a such way during prevailing west winds they are not on the leeward side of the Alps and the share of gravity wave laminae are practically the same for all stations. The same is true for the laminae induced by planetary waves. In this case all stations are practically under the same conditions. So we cannot expect large interstation differences in lamina partitioning. It will be reasonable to do this investigation at the stations which lie on the leeward side of mountains or at stations which are in hot spots of the gravity wave activity (Sacha et al., 2016). The other sources of the gravity waves are jet stream and convection (Guest et al. 2000; Yoshiki et al. 2004). Their conditions are the same for all stations used in this study. In the troposphere the stratosphere-troposphere exchange may cause the positive laminae and in the stratosphere this exchange may lead to formation of negative laminae (Kritz, 1991).

Laminae greater than 2 mPa occur very predominantly in the stratosphere where the ozone concentration is high. When the ozone concentration is high, the probability of large lamina formation increases. The confirmation of this rule is also the yearly course of PL where the maximal occurrence is observed when the ozone concentration is the highest (winter and spring). On the other hand, in the troposphere we observe neither the PL large laminae nor the large GL due to small ozone concentration. Similarly, we observe less large PL in the stratosphere in summer and fall. This dependence of the lamina occurrence on the background ozone concentration is valid only for PL, not for the gravity wave ones.

For the laminae smaller than 2 mPa the situation is different. We observe the differences in the vertical distribution of PL and GL. In winter the maximal occurrence is observed in the lower stratosphere in the case of PL, while gravity wave laminae have its occurrence maximum in the tropopause. In spring the small GL maximum lies lower than in winter. In summer the occurrence distribution has bimodal structure with one maximum in the troposphere and the other one in the stratosphere. In fall the stratospheric mode is dominant.

In summer and fall there is no polar vortex. Vortex remnants (Durry et al., 2005) may form the positive laminae in the stratosphere while the advection of air from low latitudes (Koch et al., 2002) creates layers with the low ozone concentration.

In the troposphere the situation is different. Positive laminae are created by various processes: the stratosphere-troposphere exchange (Manney et al., 2000), the advection of polluted air from the boundary layer (Oltmans et al, 2004; Collete et al., 2005) or in situ ozone production (Li et al., 2002). Tropospheric gravity waves occur predominantly in the transition region from the troposphere to the stratosphere where there is a strong change in the atmospheric stability

Our paper is based on the lamina searching procedure introduced by Teitelbaum et al. (1995). In their paper no climatological results are presented. They illustrated the method for partitioning of laminae for several case studies. The goal of our paper is to use this method for obtaining the climatological results from the mid-Europe ozonosonde stations. Similar searching method was used by Grant et al. (1998) and Pierce and Grant (1998) but for tropical and low latitudes stations. The authors found rare occurrence of PL and majority of laminae was induced by gravity waves. We found more PL compared to the gravity induced ones, because our investigation was done in middle latitudes, not in the low and tropical ones. The activity of planetary waves is stronger in mid latitudes compared to the low and equatorial ones.

5. Conclusions

The main results of this paper are:

- The most often the laminae are induced by the planetary wave activity (45-50 %), following by the indistinguishable ones (about 40 %). The share of the gravity wave laminae is about 10 %.
- There is a pronounced annual variation in the occurrence frequency of PL, while there is no such variation for GL
- With increasing lamina size the share of gravity wave and indistinguishable laminae decreases while the share of the planetary wave laminae increases.
- The vertical distribution of lamina number for large laminae has maximum in the stratosphere while the distribution of small laminae is type and season dependant.
- There are huge differences in trend patterns of PL and GL in the period 1970-2016.

Competing interests

The author declare that he has no conflict of interest

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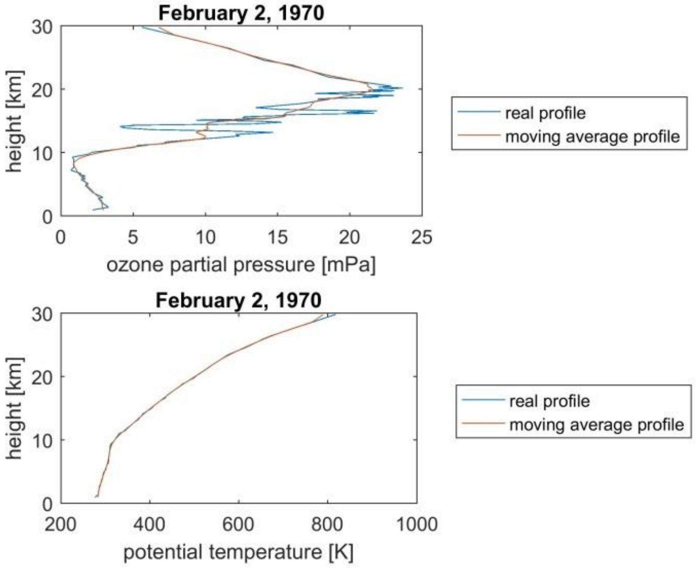

Figure 1: Real and smooth ozone (upper panel) and potential temperature (lower panel) vertical profile at the Hohenpeissenberg from February 2, 1970.

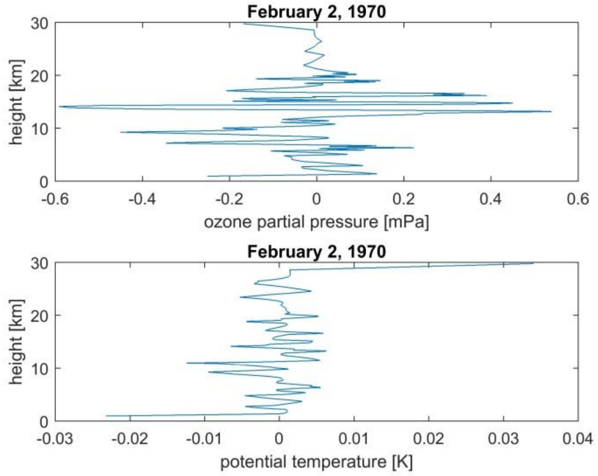

Figure 2: Differences between real and smooth vertical profile from February 2 , 1970 for ozone (upper panel) and potential temperature (lower panel)

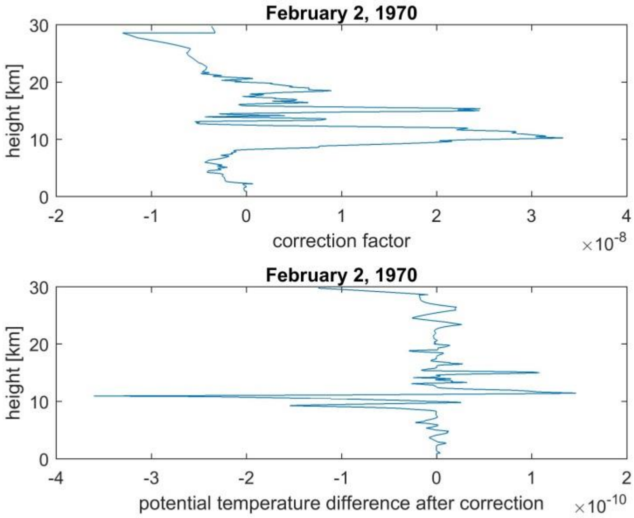

Figure 3: Vertical profile of potential temperature correction factor (upper panel) and vertical profile of differences between real and smooth potential temperature profile (lower panel) after correction.

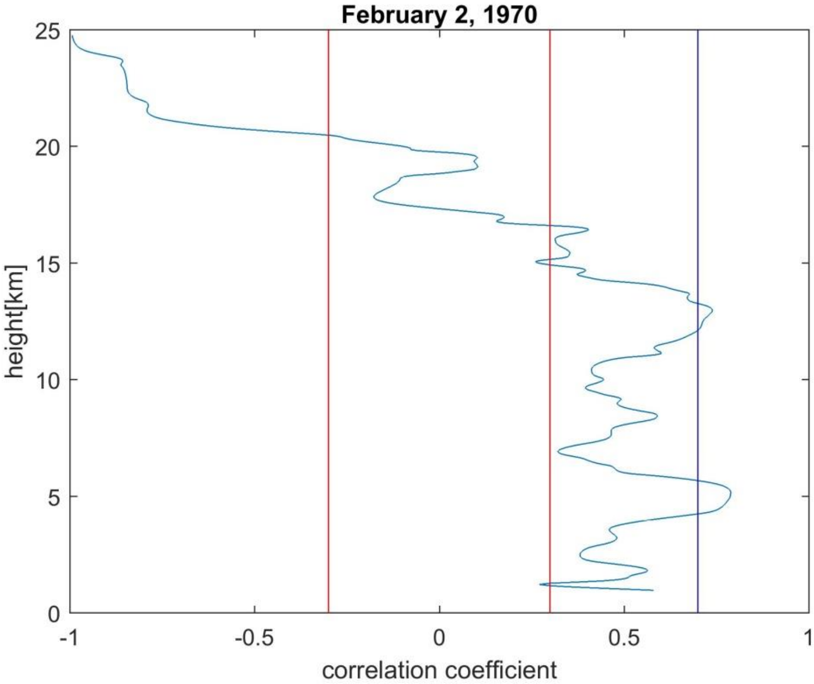

Figure 4: The vertical profile of correlations between the corrected potential temperature differences and the ozone differences from February 2, 1970 at Hohenpeissenberg. The red

vertical lines are the borders for the laminae induced by the planetary waves and the blue vertical line is the border for gravity wave ones.

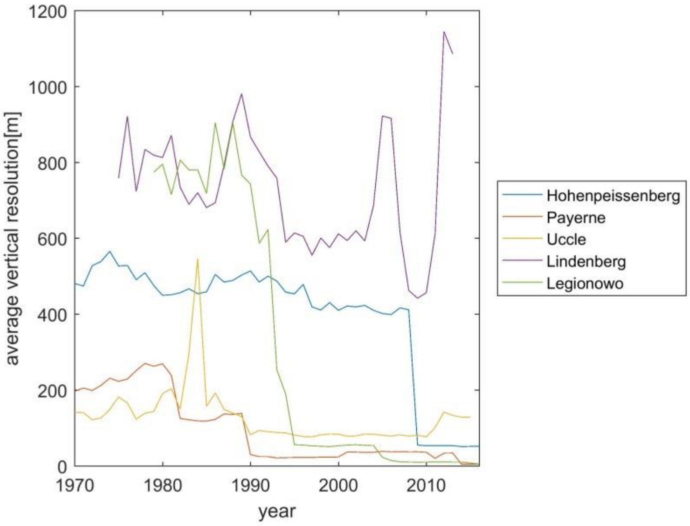

Figure 5: Long term evolution of average vertical resolution of profiles at the European ozonesonde stations.

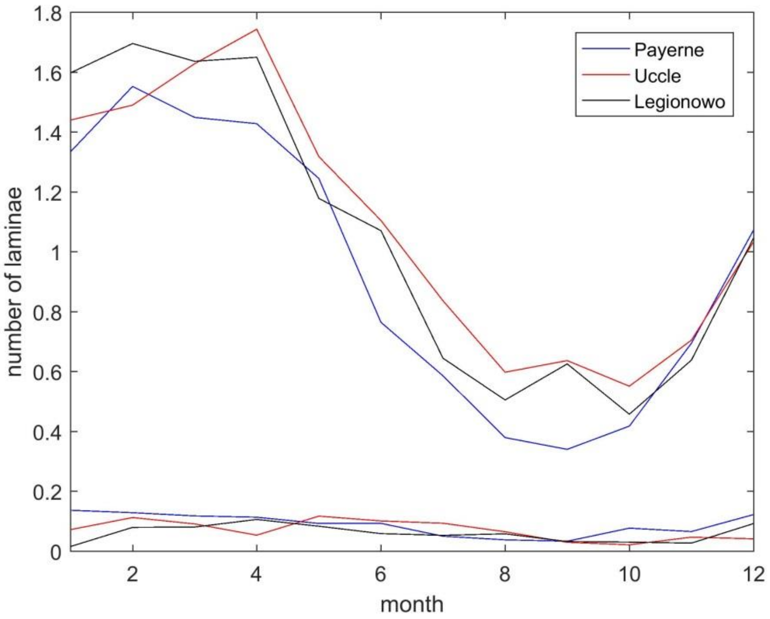

Figure 6: The annual variation of the lamina number per ozone profile for PL (group of lines with the strong variation) and for GL (group of lines with the weak variation) at the European ozonosonde stations.

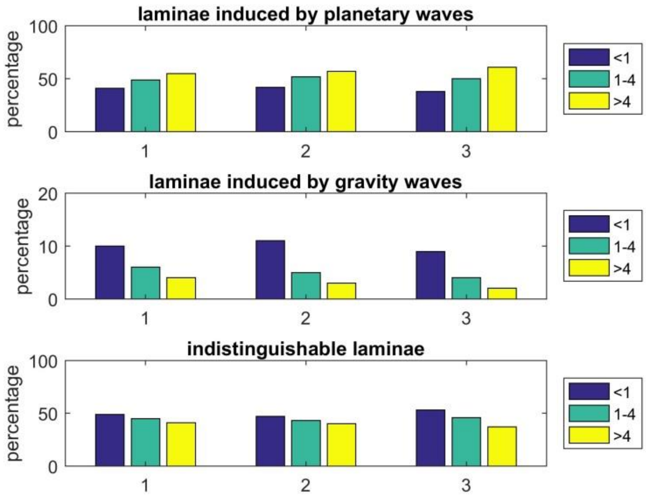

Figure 7: The dependence of the lamina composition on a lamina size for PL (upper panel), GL (middle panel) and indistinguishable laminae (lower panel) at the European stations (1-Payerne, 2 – Uccle, 3 –Legionowo)

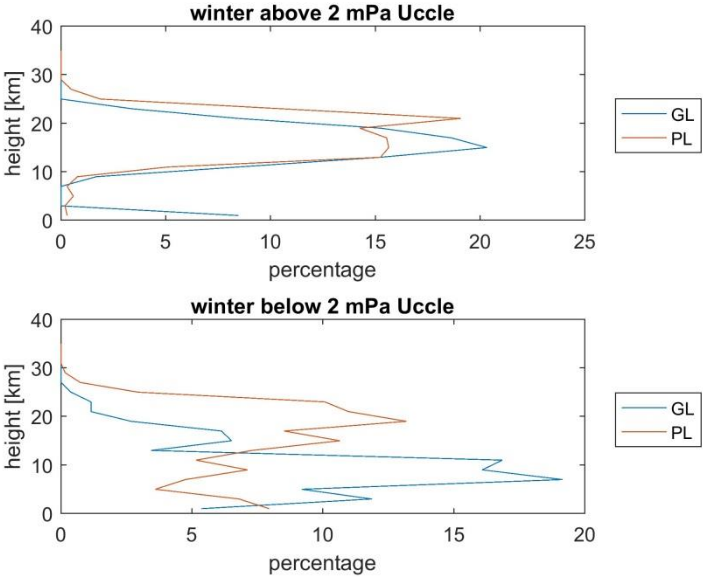

Figure 8: The vertical dependence of the occurrence of the laminae induced by the gravity waves and the ones induced by planetary waves at Uccle the period 1995-2016 in winter in terms of percentage of all GL and all PL.

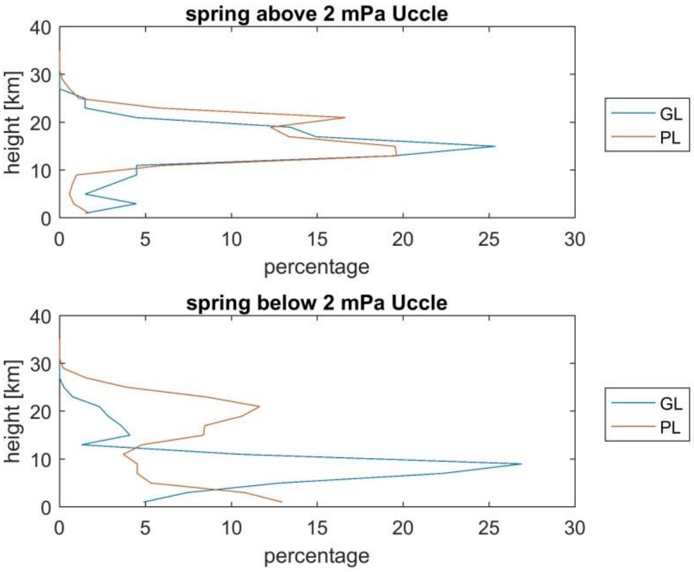

Figure 9: The same as fig.7 but for spring

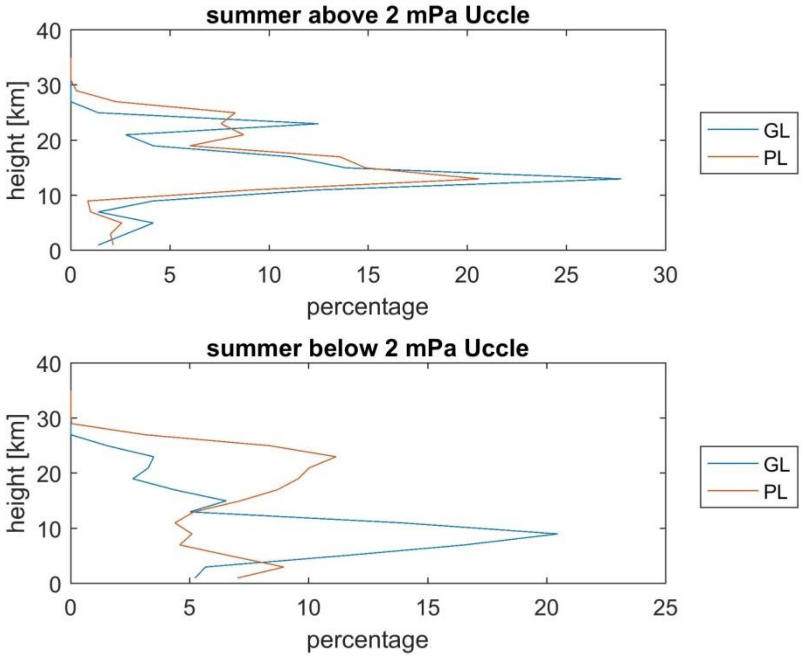

Figure 10: Vertical dependence of lamina occurrence in summer.

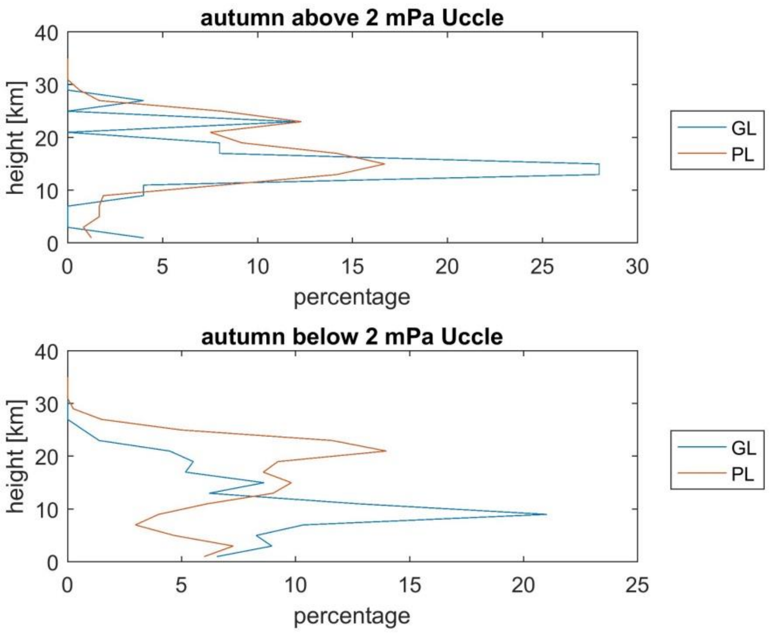

Figure 10: The same as fig. 9, but in autumn.

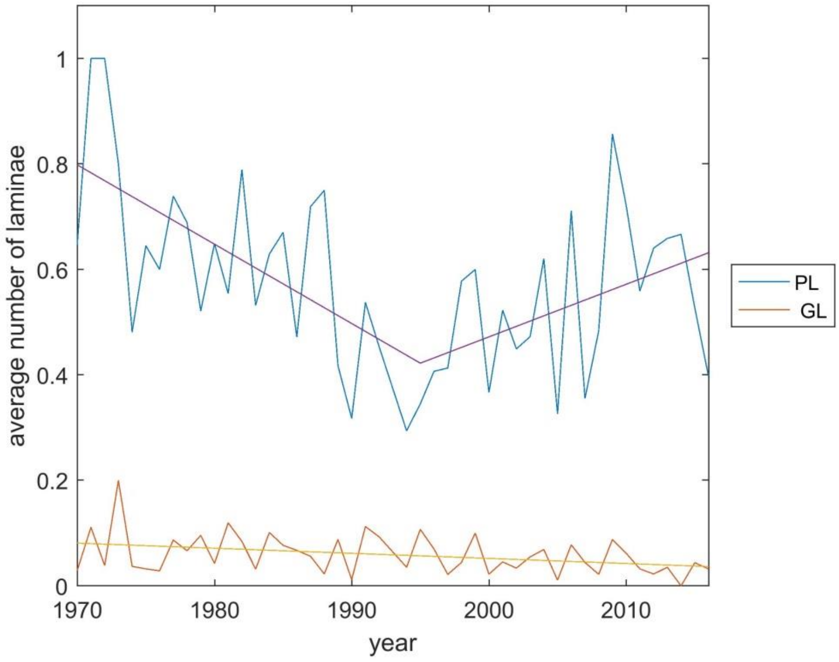

Figure 11: Trend of the number of laminae per ozone profile induced by the planetary waves (PL) and by the gravity waves (GL) for laminae greater than 4 mPa at Hoheinpeissenberg in the period 1970-2016.

	January	February	March	April	May	June	July	August	Sept	Oct	Nov	Dec
advect	48	49	48	48	45	41	44	46	47	46	47	48
gravity	10	10	11	10	11	11	10	11	10	11	9	10
undist	42	41	41	42	44	48	46	43	43	43	44	42

Table 1: Monthly composition of laminae (%) at Hohenpeissenberg in the period 1970-2016 (advect- advection laminae, gravity – gravity waves laminae, undist- undistinguishable laminae)

	<1mPa	1-4 mPa	>4 mPa
Hohenpeissenberg	**-0.95 /-0.68**	**-0.57/0.55**	-0.09/**0.25**
Payerne	**-0.49/-0.37**	**-0.50/0.29**	**0.32/0.58**
Uccle	**-0.66/-0.61**	**0.57**/-0.07	0.00/0.16
Lindenberg	**-0.79/-0.51**	**-0.88/-0.54**	**-0.76**/0.14
Legionowo	**-0.81/-0.80**	**-0.77**/-0.07	**0.31**/0.19

Table 2: Correlation coefficient of lamina number and average vertical resolution at the European mid latitudes stations from the period 1970-2016 (before slash - advective laminae, after slash – gravity wave laminae). Significant correlation coefficient values are in bold.

	<1 mPa	1-4 mPa	>4 mPa
Hohenpeissenberg	198/203	733/1021	1895/2057
Payerne	112/144	486/597	1874/1803
Uccle	121/206	486/761	1832/1775
Legionowo	104/142	535/702	1909/1983

Table 3: Average lamina depth (m) in the selected lamina size intervals at the European midle latitude stations for the vertical resolution below 100m (before slash - advective laminae, after slash – gravity wave laminae).

	till 1995	change in 1995	after 1995
PL	**-18**	**36**	18
GL	-16	-4	-20

Table 4: Results of piecewise linear regression applied to the yearly means of the large lamina number in the period 1970-2016 at the station Hoheinpeissenberg. The trend is expressed as a percentage per 10 years. Significant trends are expressed in bold.