Interactive comment on "Assessing the role of planetary and gravity waves on the vertical structure of ozone over central Europe" by Peter Križan –reviewer 1

The manuscript describes statistics of the lamina appearance in the ozone vertical distribution in dependence of the lamina origin (due to planetary or gravity waves). Thus the subject is well suited to the journal scientific profile. The author uses the methodology elaborated by Teitelbaum et al (1995) to classify the lamina based on the correlation coefficient between vertical profiles of ozone and potential temperature. The reviewer has found interesting and worth publishing results. However, there is a serious problem with selection of the profile data. Thus, the manuscript is not ready for publishing. It may have potential after additional work and resubmission. Table 3 clearly shows that the vertical resolution of the profile should be lower than 100 m for proper identification of the lamina with size less than 1 mPa and less than 500 m for the lamina size in the range 1-4 mPa. Figure 12 illustrates strong inhomogeneity of the vertical resolution for all the stations. The same is also seen from Table 2. Lindenberg profiles should be excluded from the analysis because of the large and variable vertical resolution. Thus, the analysed data are not homogeneous that may influence the results. A scale of this effect needs to be evaluated in the revised paper or only the latest results with the high resolution of the ozone profiles should be a subject of analysis. It means that the results shown in Fig.6 should be valid for only two stations since 1990 for the lamina size < 1mPa. For laminae in the range 1-4mPa the analyses will be possible for 3 stations since 1970. Thus in present form Fig. 6 is wrong especially for Lindenberg.

We excluded the station Lindenberg from the paper and we use only the stations Payerne, Uccle and Legionowo  in the period 1995-2016 where the vertical resolution of the ozone profile is about 100 m.

Minor problems: l.1-2.The title is not proper: Hohenpeissenberg, Payern, and Uccle are located in the western part of Europe. It is better to change the title to "the midlatitudinal Europe".

The title of the paper was changed

l.112-116. Have you excluded from the analyses evidently wrong profiles with the correction factor far from 1 ( a case for early Legionowo and Lindenberg ozone profiles)?

These  profiles  were excluded from the analyses.

l.158- 185. This section should be rewritten. In fact, Hohenpeissenberg profiles are not proper for analyses of laminae with size <2 mPa as for almost the whole period the vertical resolution is~500 m (see Fig.12). The Hohenpeissenberg data are proper for analysis of the laminae with the size > 2 mPa. The author could not state that similar results were derived for other stations, as for Lindenberg (all observations) and Legionowo (early observations before 1990) were not possible to identify correctly lamina with the size <2 mPa.

We use here the station Uccle in the period 1995-2016, so this problem is solved.

l. 190 -197. Trend values should appear (% for 10 yr.) with their error estimates to discuss the trend significance. The two-joint lines trend model with the turning point in the mid1990s needs to apply also for the gravity waves laminae for better comparison with PL laminae. If you calculate the trend based on single line approach for the PL laminae you will probably result with small negative trend as you discussed for the case of the GL lamina trend.

From figure 11 we see principally different trends for PL and GL. So the piecewise regression is suitable only for Pl laminae.  This regression is not suitable for GL. In this case it gives insignificant trend before 1995 and insignificant change in 1995. On the other hand the classical regression is erroneous for PL and the most suitable for GL where it gives significant negative trend.

l. 215- 220. The discussion is not correct for Payern as this station is located in the valley between the Jura Mountains and Alps.

This sentence was changed.

Thank you for all your comments. They make my paper better.

Interactive comment on "Assessing the role of planetary and gravity waves on the vertical structure of ozone over central Europe" by Peter Križan

Anonymous Referee #2

Based on the Teitelbaum method, this manuscript studies the characteristics of ozone lamina under the influence of planetary and gravity waves. This article seems to have done a lot of work. Even though I'm not an expert in this area (ozone lamina), there are a few things that make me confused.

Major comments: 1 The formation mechanism of ozone lamina. Tomikawa et al. (2002) reported that the formation of the ozone laminae is closely related to the vertical shear of the subtropical jet. I strongly suggest the authors to discuss in the introduction about the formation mechanisms of the ozone lamina and in which the role of wave activities play. Tomikawa, Y. , Sato, K. , Kita, K. , Fujiwara, M. , Yamamori, M. , & Sano, T. . (2002). Formation of an ozone lamina due to differential advection revealed by intensive observations. J. Geophys. Res., 107(D10).

This paper is referred to in Discussion.

2. Lines 101-108, need some references (at least one) or make some explanation: e.g. Why choose 5-15km and 17-22km height area to distinguish. If the identification process is proposed by the author, it appears from the description that the author only uses ozone thin layers at different height region to define whether the ozone laminae is caused by gravity or planetary waves. This makes it very puzzling because gravity waves almost exist anywhere in the earth's atmosphere.

I did the research for all heights from the ground to the 5 km below the highest profile point. The intervals 5-15 km and 17-22 km were chosen because the correlation here is sufficiently high (above 0.7) or low (below 0.3) for detection of gravity and planetary waves. In these intervals the ozone profile are **strongly** influenced by atmospheric waves. Outside these intervals   the profile is not so strongly influenced as in these intervals. The atmospheric waves can occur outside intervals, but they do not influence the ozone vertical profile.

3. The authors have only mentioned the thin layer of ozone caused by gravitational and planetary waves, but I think that some other meso-and small-scale atmospheric processes (such as strong convection, tropopause folding, strong wind shear, stratospheric streamers, etc.) may also responsible for the formation of ozone laminae.

Various mechanisms of lamina formation is described in the Discussion

4. Gravity and planetary waves run through the title and the paper, but there is no evidence of their existence in the manuscript (even though the authors indicate that the ozone profile can be used to detect fluctuations)

This title of paper was recommended by editor.

5. Reading the manuscript, I still didn't understand how gravity and planetary waves affect and lead to ozone laminae. Personally, a detailed case is necessary.

This problem is theoretically solved in Teitelbaum paper.

Minor comments: 1. Lines 44-46, as you mentioned, it is the large lamina that has a close correlation with the total ozone content, not the narrow lamina. The actual significance of narrow lamina still not clear throughout the manuscript.

We were interested in laminae of various sizes because according to theory gravitational waves produce predominantly small size laminae. On the other hand planetary waves are able to form also the large laminae.

2. Lines 47-48, needs relevant references (at least one),especially about the influence of waves on the laminae.

The references were given in the Introduction.

3. Line 75 from->on ?

4. Line 76 for the approximating-> for approximating

This grammar mistakes were corrected

5. Line 125 partitioning of laminae-> partitioning laminae?

We can say partitioning of laminae or lamina partitioning but not partitioning laminae

6. Conclusion: as mentioned in the introduction, if the Teitelbaum method is suitable for central Europe?  And how well?

Teitelbaum method was demonstrated for data at the Sodankyla (northern Finland) and this method was able to detect atmospheric waves in the ozone profile. Grant et al. (1998) used the same method for the tropical station\s  and this method brought  reasonable results. So we suppose this method is suitable also for the stations in Europe, because we obtained results which were expected in the case of well working method.

The reviewer noticed substantial improvement of the manuscript. However, several minor corrections/additions are necessary to meet quality of the journal.

Minor corrections

1. The remnants of the previous title (…. Central Europe) survived in the new text.

Replace central Europe to midlatitudinal Europe in the whole manuscript, e.g. l.170, 203, 204, 397.

All remnants were replaced.

2. In abstract, PL frequency is 3-5 times larger than GL (l.172) but in the main text the ratio is "about 4-6" (l.391). Which one is correct? Figure 7 provides that the ratio is around 5 for small lamina but increases for larger lamina, and for large lamina the ratio is about 10. Please provide the values of the ratio for all lamina classes. It is not enough to say that " with the increasing lamina size the share of GL decreases and the share of PL increases" (l.174-175).

I did table which displayed the ratio of PL and GL in each month and station used in paper and the results are discussed in paper.

3. L.175-176. Consider changes in the statement: "The vertical profile of lamina occurrence is different for small planetary wave and gravity wave laminae". Use abbreviations PL and GL. The difference concerns all (large/small) laminae. Be more precise and define what the mentioned difference is and how it depends on lamina size?

We did it

4. l. 238 "the average ozone profile (potential temperature)" Please define meaning of the "average" i.e. the mean for month, season, year etc.

5. l.245. Start new line beginning with "In each point……"

6. l.293-294 Consider rewriting: " If these correlations are significant the resolution influences the lamina number and vice versa". Delete "and vice versa" In fact, number of lamina does not affect technical issue of the ozone-sonde resolution.

7. l.295. The results are shown in Table 2 not in Table 1.

8. L. 646 and l. 651. Tab.1 and Tab.2 . Term advective lamina is used. It should be PL.

9. l.301. It should be Tab.3 instead Tab.2.

10. l.308-310. Delete these lines and start with "The vertical resolution of sonde measurements must be….." Please add "measurements" after "sonde".

11. l.311. It should be Table 3 instead Tab.2.

Points 4-11 were changed according to reviewer suggestions.

12. l.325-326. It is better to say that "Annual variation with the maximum in winter/spring and summer/autumn minimum is clearly seen for PL but this pattern is very weak in case of GL". Section 3.3 is very short, so add some comments that the maximum is about 4 times higher than the minimum in case of PL. Please also discuss the yearly mean values in both cases.

We did it

13. L.323 and l. 332 – It should be different numbers not both 3.3. Further changes are needed for all subsection numbers in section 3.

14. L.628. Here Figure number should be 11

15. Fig8-Fig.11 . For better comparison the range of X axis should be the same for all figures, e.g. [0,30].

Points 13-15 were changed according to reviewer suggestions.

16. Section 3.4. The results are shown for Uccle only.  The reviewer would like to see results for Payerne as this station is located in the valley between the Jura Mountains and the Alps and it seems that GL profile will be different in the troposphere.

We show the results for the station Payerne, but these results were not different from the other stations.

17.  There is a serious problem with section 3.5 – Trend of large laminae Why only the results from Hohenpeissenberg have been analysed? There is possibility of trend analyses of all types of laminae for Uccle and Payerne starting in 1990 and for Legionowo starting in 1995. Simple linear regression should be used in this case. For comparison purposes it is better to focus on trend for the period 1995-2016.

Piecewise approach is valid for longer data- Hohenpeissenberg 1970-2016. Here you present trend results for only one station. It is not mentioned in the abstract, conclusions, and in section 3.5. You cannot envisage that similar trend patter appears for other stations. Moreover, the trend analysis is not mentioned in section 4 (Discussion). Your trend analysis should contain more stations even with shorter data if your interest is the long-term lamina variability over the midlatitudinal Europe. My recommendation is to delete this section and omit discussion concerning the trends (l.176-177) and l. 462.  More comprehensive analysis of long-term variability of laminae over the midlatitudinal Europe is a good subject for next your paper.

Trends of laminae was deleted from the paper.

 18. L.425. Be more precise. What is the meaning of small GL maximum? Another maximum or the maximum for small GL(<2hPa)?

19. L.425-427. " In summer the occurrence ...... It is not clear what kind of laminea you describe here, GL or PL. For me it seems that is valid only for PL.  It is better to limit the discussion to apparent maxima as you have a plenty of secondary extremes.

20. L.424-425 "occurrence maximum is observed in the tropopause". It is better to say near tropopause as you have no info about the tropopause height.

The paragraph concerning the vertical profile of lamina occurrence was rewritten.

21. L403-405. At this point the reviewer would like to see a discussion of gravity waves over Payerne (a site between the Jura Mountains and the Alps). See also problem no.16.

We discuss this topic in the paper.

**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 midlatitudinal 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 10-20 times more frequent than that of GL. 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 PL and GL smaller than 2 mPa. For laminae greater than 2 mPa this difference is smaller.*

**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 midlatitudinal Europe in the period 1970-2016. At first we test if the Teitelbaum method is suitable for such research. 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 $O_{3avg}$ ($\Theta_{avg}$) is the average ozone partial pressure (potential temperature) 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. 1. 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. 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.2. 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.

The vertical resolution of sonde measurements must be comparable or smaller than the average depth of laminae and thus one can see (table 3) 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 annual variation with maximum in winter/spring and summer/autumn minimum is clearly seen for PL but this pattern is very weak in case of GL. Monthly values of the ratio of the number of PL and GL at the European midlatitudinal stations are given in table 4 for laminae greater than 2 mPa. We see this ratio is month dependant On average its value is from 10 to 20, but in January at Legionowo its value is nearly 100. We think it is an outlier.  The number of PL is much higher than that of GL.  This different behaviour of the annual variation is the evidence that the both type of laminae are formed by different processes.

**3.4. 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).

**3.5. 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 Payerne, 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. Similar behaviour is seen in spring (fig.9), where we observe strong small GL occurrence maximum in the troposphere. In spring small PL have the maximal occurrence in the lower stratosphere. 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. We observe broad stratospheric maximum in small PL occurrence in summer, while the small GL have bimodal vertical profile with one maximum in the troposphere and the other maximum is present in the stratosphere. In autumn (fig.11) the maximum in occurrence of small PL and GL laminae is observed in the stratosphere.

## 4. Discussion

We found the occurrence frequency of PL to be about 10-20 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 midlatitudinal 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.

In this paper we were interested in PL and GL laminae which can be detected from the ozone profile. We evaluated the vertical profile of the PL and GL occurrence at Payerne. This station is situated in the valley between the Alps and Jura mountains. Behaviour of PL is given by the activity of planetary waves and thus there is no reason for which we can expect special behaviour of PL at this station. In the case

of GL, the most important thing which governs GL behaviour is orography. The Alps are situated to the east (southeast) from the station so during prevailing west winds the most important feature of orography is Jura mountains which is not high enough for generating strong gravitational waves in the stratosphere. We can speculate some of GL in the troposphere may have its origin in Jura mountains.

**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.

**Competing interests**

The author declare that he has no conflict of interest

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**Acknowledgement**
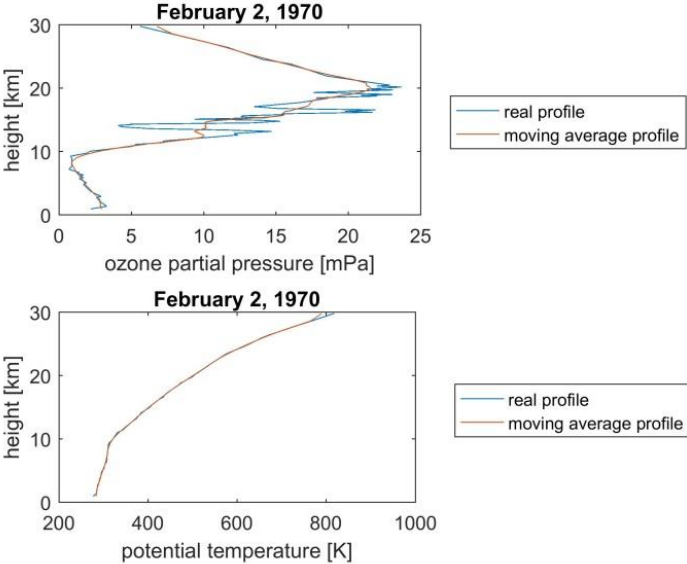
# References

Bird, J.C., Pal, S.R., Carswell, A.I., Donovan, D. P., Manney, G.L., Harris, J.M., and Uchino, O.: Observations of ozone structures in the Artic polar vortex. J. Geophys. Res., 102, D9, 10,785-10, 800, 1997.

Collete, A. and Ancellet, G.: Impact of vertical transport processes on the tropospheric ozone layering above Europe. Part II: Climatological analysis of the past 30 years. Atmos. Environ. 39, 5423-5435, 2005.

Dobson, G., M., B.: The laminated structure of the ozone in the atmosphere. Quart.  J. R. Met. Soc. 99, 599-607, 1973.

Durry, G. and Haucherone, A.: Evidence for long-lived polar vortex air in the mid-latitude summer stratosphere from in situ laser diode $CH_4$ and $H_2O$ measurements. Atmos. Chem. Phys. 5, 1697-1472, 2005.

Guest, F. M., M. J. Reeder, C. J. Marks, and D. J. Karoly: Inertiagravity waves observed in the lower stratosphere over Macquarie Island, J. Atmos. Sci., 57, 737– 752, 2000.

Grant, W.B., Pierce, R.B., Oltmans, S.J. and Edward, W.: Seasonal evolution of total and gravity waves induced laminae in ozonosonde data in the tropics and subtropics, GRL., 25,11, 1863-1866, 1998.

Kar, J., Trepte, C.R., Thomason, L.W. and Zawodny, J. M.: Observations of layers in ozone vertical profiles from SAGE II (v 6.0) measurements, Geoph. Res. Lett, 29, NO 10, 10.1029/2001GL014230, 2002.

Koch, G., Wernli, H., Staehelin, J. and Peter, T.: A Langrangian analysis of stratospheric ozone variability and long-term trends above Payerne (Switzerland) during 1970-2001. JGR, 107, D19, 437, doi: 10.1029/2001JD001550, 2002.

Kritz, M.A., Rosner, S.W., Danielsen, E.F. and Selkirk, H.B.: Air mass origins and troposphere to stratosphere exchange associated with mid-latitude cyclogenesis and tropopause folding inferred from [7]Be measurements. J. Geophys. Res., 96, D9, 17,405-17,414, 1991.

Križan, P. and Laštovička, J.: Definition and determination of laminae in ozone profiles. Studia geoph. et geod., 48, 777-789, 2004.

Križan, P and Laštovička, J.: Trends in positive and negative ozone laminae in the Northern Hemisphere. J. Geophys. Res., D 10107, doi: 10.1029/2004JD005477, 2005.

Laštovička, J. and Križan, P.: Trends in laminae in ozone profiles in relation to trends in someother middle atmospheric parameters., Physics and Chemistry of the Earth, 31, 46-53, 2006.
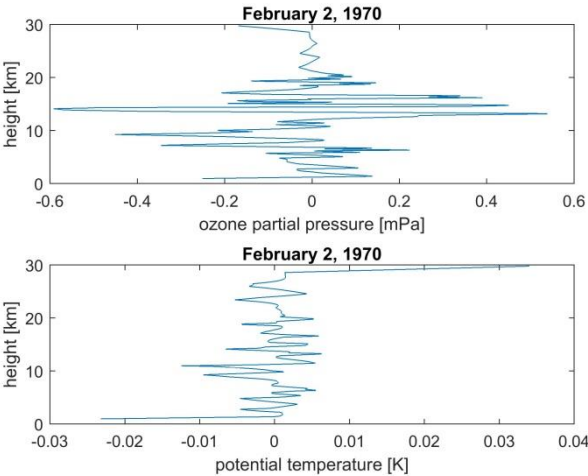
Li, Q. et al.: Stratospheric versus pollution influences on ozone at Bermuda: Reconciling past analyses. JGR, 107, D 22, 4611, doi: 10.1029/2002JD002138, 2002.

Manney, G. L., Michelsen, H. A., Irion, F. W., Toon, G. C., Gunson, M.R. and Roche, A. E.: Lamination and polar vortex development in fall from ATMOS long-lived trace gases observed during November 1994. J. Geophys. Res., 105, D23, 29,023-29,038, 2000.

 Oltmans, S. J., Johnson, B. J., Harris, J. M., Thompson, A. M., Liu, H. Y., Chan, C. Y.,  Vömel, H., Fujimoto, T., Brackett, V. G., Chang, W. L., Chen, J. P. Kim, J. H.,

Chan, L. Y.and  Chang, H. W.,: Tropospheric ozone over the North Pacific from ozonosonde observations:  JGR, 109, D15801, doi: 10.1029/2003JD003466, 2004.

Orsolini,Y., Simon, P. and Cariolle, D.: Filamentation and layering of an idealized tracer by observed winds in the lower stratosphere. Geoph. Res. Lett, 22, No. 7, 839-842, 1995.

Orsolini, Y.J., Hansen, G., Hoppe, U. P., Manney, G.L. and Fricke, K.H., : Dynamical modeling of wintertime lidar observations in the Artic: Ozone laminae and ozone depletion. Q.J.R. Meteorol. Soc., 123, 785-800, 1997.

Orsolini,Y.J., Hansen, G., Manney, G.L., Livesey, N. and Hoppe U.P.: Lagrangian reconstruction of ozone column and profile at the Artic Lidar Observatory for Middle Atmosphere Research (ALOMAR) throughout the winter and spring of 1997-1998. J. Geophys. Res., 106, D 9, 10011-10021, 2001.

Pierce, R.B. and Grant, W.B.: Seasonal evolution of Rossby and gravity wave induced laminae in oznosonde data obtained from Wallops Island, Virginia, Geoph. Res. Lett. 25,11, 1859-1862,1998.

Reid, S.J. and Vaughan, G.: Lamination in ozone profiles in the lower stratosphere, Q.J. R. Met. Soc., 117, 825-844, 1991.

Sacha, P., Lilienthal, F., Jacobi, C., and Pisoft, P.: Influence of the spatial distribution of gravity wave activity on the middle atmospheric dynamics, Atmos. Chem. Phys., 16, 15755-15775, doi:10.5194/acp-16-15755-2016, 2016.

Smith, R.B., B.K. Woods, J. Jensen, W.A. Cooper, J.D. Doyle, Q. Jiang, and V. Grubišić: Mountain Waves Entering the Stratosphere. *J. Atmos. Sci.,* **65**, 2543–2562, https://doi.org/10.1175/2007JAS2598.1, 2008.

Teitelbaum, H., Moustaoui, M., Ovarlez, J. and Kelder, H.: The role of atmospheric waves in the laminated structures of ozone profiles at high latitude. Tellus, 48A, 442-455, 1995.

Teitelbaum, H., C. Basdevant, and M. Moustaoui: Explanations for simultaneous laminae in water vapor and aerosol profiles found during the SESAME experiment, *Tellus*, 52A, 190-202, 2000.

Tomikawa, Y., Sato, K., Kita, K., Fujiwara,M., Yamamori, M. and Sano, T.: Formation of an ozone lamina due to differential advection revealed by intensive observations. J. Geophys. Res., 107, D 10, 10.1029/2001/JD000386,2002.
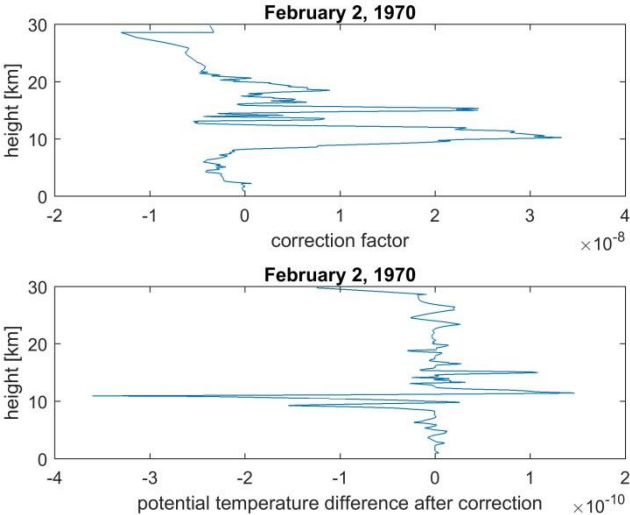
Yoshiki, M., N. Kizu, and K. Sato:  Energy enhancements of gravity waves in the Antarctic lower stratosphere associated with variations in the polar vortex and tropospheric disturbances, J. Geophys. Res., 109, D23104, doi:10.1029/2004JD004870,2004.
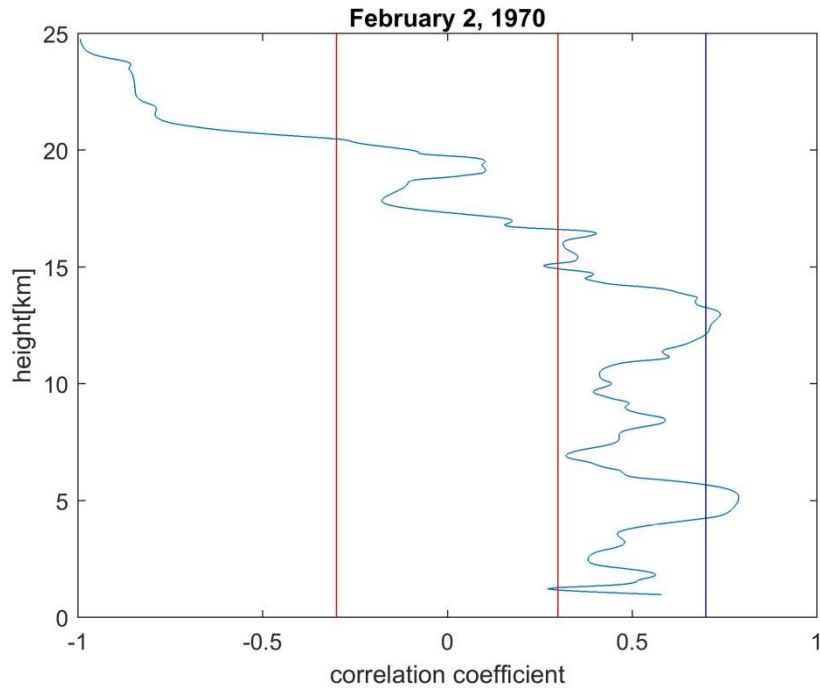
**Figure 1:** Real and smooth ozone (upper panel) and potential temperature (lower panel) vertical profile at the Hohenpeissenberg from February 2, 1970.
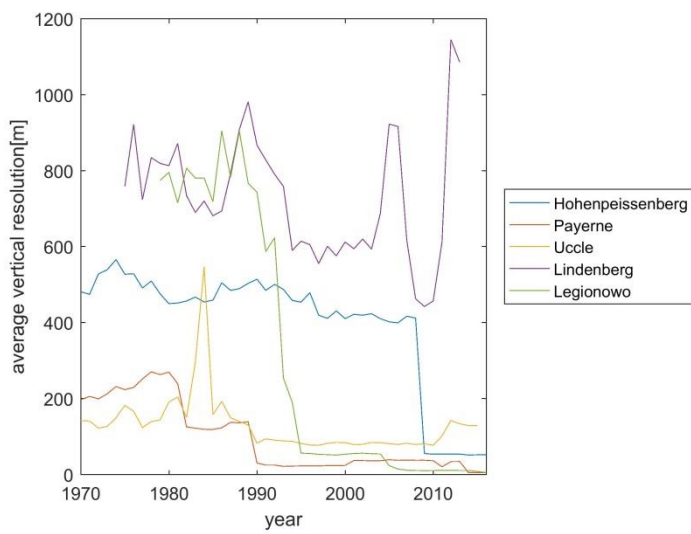
**Figure 2:** Differences between real and smooth vertical profile from February 2,   1970   for   ozone (upper panel) and potential temperature (lower panel)
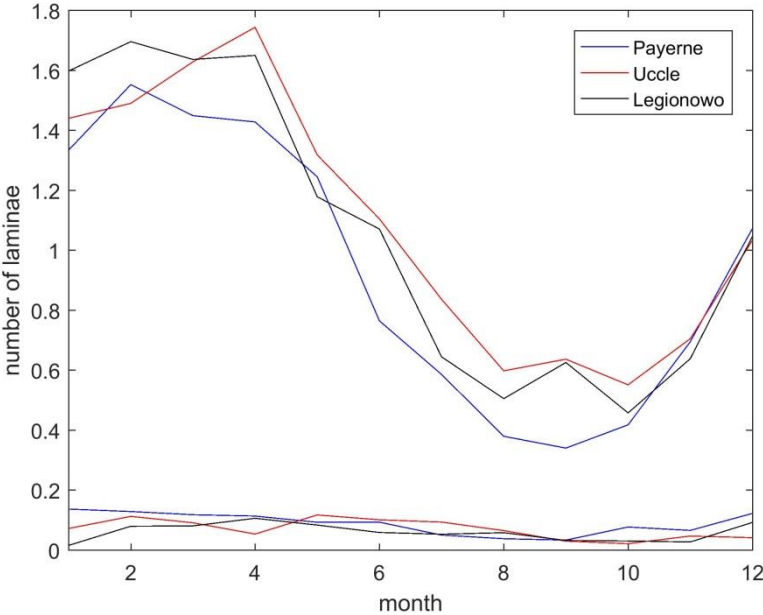


**Figure 3:** Vertical profile of potential temperature correction factor (upper panel) and vertical profile of differences between real and smooth potential temperature profile (lower panel) after correction.
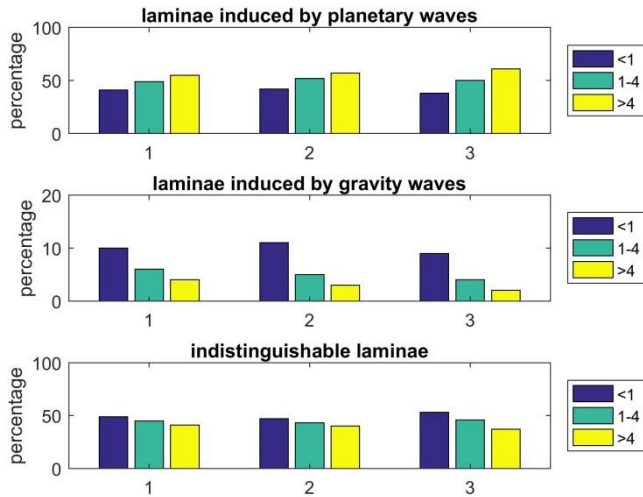
**February 2, 1970**

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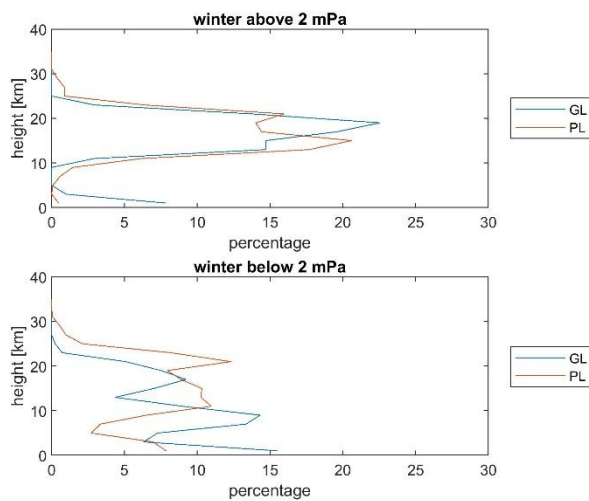
**Figure 5:** Long term evolution of average vertical resolution of profiles at the European ozonesonde stations.
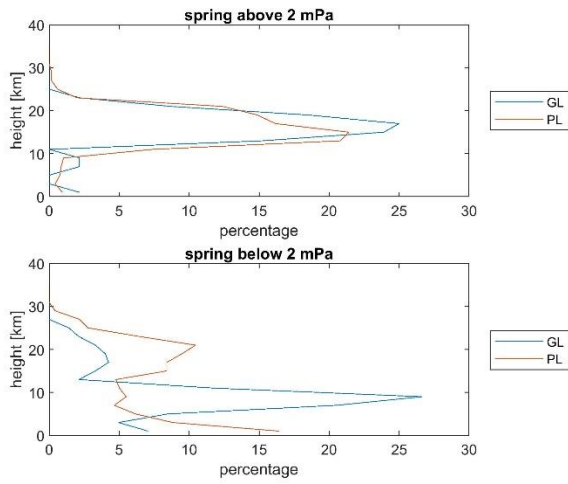


**Figure 6:** The annual variation of the lamina number per ozone profile for PL (group of lines with the strong variation) and for GL (group of lines with the weak variation) at the European ozonosonde stations.
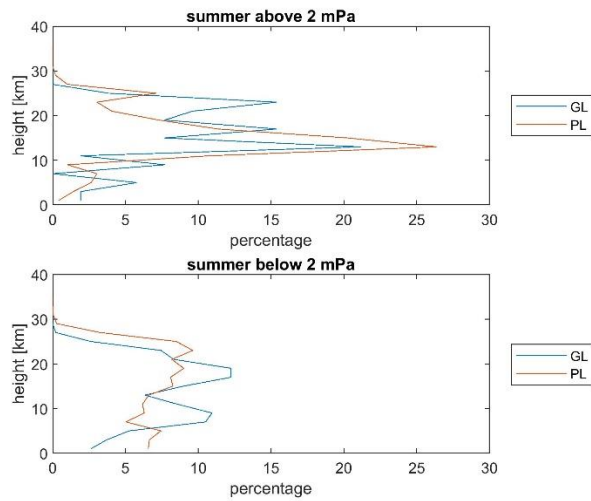
**Figure 7**: The dependence of the lamina composition on a lamina size for PL (upper panel), GL (middle panel) and indistinguishable laminae (lower panel) at the European stations (1- Payerne, 2 – Uccle, 3 – Legionowo)
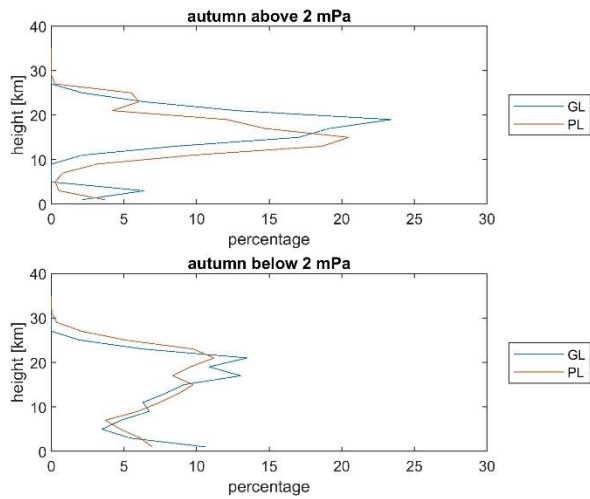


**Figure 8:** The vertical dependence of the occurrence of the laminae induced by the gravity waves and the ones induced by planetary waves at Payerne in the period 1995-2016 in winter in terms of percentage of all GL and all PL.

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



**Figure 10:** Vertical dependence of lamina occurrence in summer.

**Figure 11:** The same as fig. 9, but in autumn.

|        | January | February | March | April | May | June | July | August | Sept | Oct | Nov | Dec |
|--------|---------|----------|-------|-------|-----|------|------|--------|------|-----|-----|-----|
| PL     | 48      | 49       | 48    | 48    | 45  | 41   | 44   | 46     | 47   | 46  | 47  | 48  |
| GL     | 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 (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 - PL, after slash – GL). 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 middle latitude stations for the vertical resolution below 100m (before slash - advective laminae, after slash – gravity wave laminae).

| | I | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Payerne | 10 | 12 | 12 | 13 | 13 | 8 | 12 | 10 | 10 | 5 | 11 | 9 |
| Uccle | 20 | 13 | 18 | 32 | 11 | 11 | 9 | 9 | 21 | 25 | 15 | 25 |
| Legionowo | 98 | 21 | 20 | 15 | 14 | 18 | 12 | 9 | 19 | 15 | 23 | 11 |

**Table 4:** Monthly values of ratio of the number of PL and GL at the European midlatitudinal stations for laminae greater than 2 mPa.