DOES THE QBO AND THE MT. PINATUBO VOLCANIC ERUPTION AFFECT THE GRAVITY WAVE ACTIVITY IN THE LOWER IONOSPHERE ?

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Summary: *All existing data (~6 years) on gravity wave activity, inferred from the nighttime A3 (oblique incidence on the ionosphere) radio wave absorption measurements in the lower ionosphere on 270 kHz at Průhonice in Central Europe, have been exploited to get information on the effects of QBO phases and the Mt. Pinatubo volcanic eruption on the gravity wave activity in the winter half of the year. There appears to be an enhancement of gravity wave activity in the two winters just after the strong volcanic eruption of Mt. Pinatubo. This enhancement is remarkable for long-period waves (T = 2–3 hours). No clear effect of the phase of QBO on the level of gravity wave activity has been found; a possible effect of QBO on the correlations between gravity wave activities in individual period bands is indicated. The results are limited by a relatively short data series; however, no more data will be available.*

Keywords: lower ionosphere, gravity waves, volcanic eruptions, QBO

1. INTRODUCTION

The gravity wave activity in the lower ionosphere above Central Europe has been inferred from the digital nighttime LF radio wave absorption measurements for about six years. These data are used to estimate the effect of the Mt. Pinatubo volcanic eruption on the gravity wave activity in the above area and to search for the equatorial stratospheric wind quasi-biennial oscillation (QBO) effect on gravity wave activity.

The effects of QBO have been reported to occur in various parameters of the extratropical middle atmosphere including ozone (e.g. *Labitzke and van Loon, 1988*; *Balachandran and Rind, 1995*; *Yang and Tung, 1995*; *Randel and Wu, 1996*) and in the lower ionosphere (e.g. *Laštovička and Knyazev, 1990*). On the other hand, there are some parameters in the extratropical middle atmosphere, which display an extremely large annual variation and no detectable QBO signal, such as the planetary wave activity in the upper middle atmosphere (*Laštovička, 1993*) and laminae in ozone profiles in the lower stratosphere (*Mlch and Laštovička, 1996*).

The eruption of volcano Mt. Pinatubo in June 1991 was followed by a temporary cooling of the troposphere (e.g. *Kawamata et al., 1993*) as expected from the effects of past events (e.g. *Crowley et al., 1993*). It also affected the temperature of the lower stratosphere in the form of an initial increase (*Labitzke, 1994*), followed by a delayed slight decrease due to ozone reduction (e.g. *Randel et al, 1995*). Mt. Pinatubo-related heating was observed also in the middle stratosphere (30 hPa; *Labitzke et al., 1995*). A significant depletion of stratospheric ozone has been observed as well as modelled (e.g. *Randel et al., 1995*; *Tie and Brasseur, 1995*). This depletion peaked at middle latitudes in 1992–1993.

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2. DATA AND METHOD

The information about the gravity wave activity was obtained from the nighttime (solar zenith angle $\chi > 100°$) digital measurements of the radio wave absorption in the lower ionosphere at 270 kHz. The measurements were performed by the A3 method (oblique incidence on the ionosphere; continuous wave) at the Průhonice Observatory along a radio circuit with the following parameters: transmitter-receiver distance 236 km, reflection point 49.45°N, 16.05°E, L-shell 2.1, nighttime reflection height around 95 km. Details of the A3 method, measuring equipment, calibration, and basic data evaluation have been described by *Laštovička et al. (1993)*. The typical values of absorption are about 20 dB, the inaccuracy in the determination of absolute absorption values is no more than 1 dB, and for relative values (variations) the inaccuracy is much lower. (*Laštovička et al., 1993*).

The gravity wave activity data are available nearly continuously (with a few gaps due to technical reasons) for the period July 1988 – December 1993. Before July 1988, only analog records on paper, with a considerably lower accuracy, are available. Since January 1994, the transmitter has often been switched off for most of the night. Some information on gravity wave activity may be obtained only for October – November 1994. During 1995 the intensity of the transmitted radio waves became modulated by the intensity of sound modulation, which rendered these measurements almost useless for reliable absorption determination. The daily absorption values are strongly controlled by solar zenith angle and solar activity and, therefore, using them to compute reasonably accurate gravity wave spectra is very difficult, if not impossible.

For gravity wave analyses we use 1-min average values of the signal intensity (absorption). One spectrum in the period range of 10 min – 3(2) hours (longer periods in winter with longer nights) is routinely computed for each night by the correloperiodogram method (e.g. *Vitinsky et al., 1986*). The correloperiodogram method provides a better resolution at longer periods than other methods, e.g. Fourier analysis. The spectra are computed with a step of 1 min at shorter periods and of 2 mins at longer periods. Periods shorter than 10 min are not computed because the results are considered less reliable due to the character of input data. Statistical characteristics (correlation coefficients, standard deviations, etc) were computed using the STATGRAPHIC statistical software.

Since only deep-night data ($\chi > 100°$) are used, solar X-ray and direct EUV radiation variability cannot cause the observed gravity-wave type oscillations. The main nighttime ionizing agent, geocoronally scattered solar H Lyman-alpha flux, is stable on short time scales. Even during solar flares it changes by only a few percent. Geomagnetic storms do not affect observably the overall gravity wave activity (*Laštovička et al., 1993*), hence the geomagnetic origin of the observed gravity-wave type oscillations can be excluded. They may, therefore, be assumed to reflect the real gravity wave activity. The region where the large majority of absorption occurs at night (the last 3 – 5 km below reflection height) is much smaller than the vertical wavelength of dominant gravity waves (> 10 km, e.g. *Vincent, 1990*; *Wu and Widdel, 1992*) at altitudes of 90 – 95 km, which makes it possible to infer the gravity wave activity. However, effects of small-vertical-scale waves, which fortunately do not contribute much to the total gravity wave energy, can be smoothed out.

The problem of transformation of gravity waves in the neutral upper middle atmosphere into waves in absorption and how to obtain undoubtedly gravity waves in the neutral atmosphere from waves in absorption is very complex. *Fritts and Thrane (1990)* showed by theoretical calculations that, in a realistic upper middle atmosphere, gravity waves with periods of about 0.5 – 5 h displayed a frequency-dependent phase shift between waves in the neutral and ionized components, mainly due to chemical relaxation effects. The absorption is determined by a combination of electron density and collision frequency (proportional to atmospheric pressure); gravity waves in them are not in phase. Moreover, our experimental output consists of one average spectrum per night, which means a necessary smoothing and possible mixing of individual waves. Therefore, an unambiguous interpretation of individual waves in absorption spectra in terms of individual waves in the neutral atmosphere is practically impossible. Even in the ionospheric F-region, where the situation seems to be easier, the direct computation of gravity waves in the thermosphere from travelling ionospheric disturbances (TIDs) in the ionosphere is almost impossible even with EISCAT measurements and the opposite procedure, calculating the model TIDs from model gravity waves and fitting the observed TIDs to model TIDs (*Schlegel, 1997*). Thus only the gross features, such as long-term changes of gravity wave activity in a period band, can be described by absorption-inferred gravity wave data reasonably well, whereas short-term changes and fine details are much less certain.

Multipoint and multimethod measurements of the gravity wave activity over Europe and Canada during the international campaign DYANA (January – March 1990; DYnamic Adaptive Network for the Atmosphere), which included our absorption-inferred gravity wave data, showed that there was a large variability in the day-to-day gravity wave activity and a rather fast decorrelation of gravity wave activities as a function of altitude difference or horizontal distance (*Hauchecorne et al., 1994*). The general long-term pattern was found to be fairly similar for various altitudes but still different for horizontal distances of several hundred kilometres (*Hauchecorne et al., 1994*). Thus the results obtained in this paper do not necessarily apply to other more distant locations.

The whole interval of 10 min – 3 h is divided into six subintervals, 10 – 30, 31 – 60, 61 – 90, 91 – 120, 121 – 150 and 151 – 180 mins. The spectral maxima (amplitudes) in the individual intervals of individual nights are considered to be a measure of gravity wave activity. More sophisticated measures of gravity wave activity provide the same general pattern (not all details, of course) of gravity wave activity (*Laštovička et al., 1993*). Therefore, it is sufficient to use maximum amplitudes. Anyway, fine details are not considered reliable in view of the nature of input data. Figure 1 shows an example of the development of gravity wave activity over January – March 1992.

The QBO-phase information is based on the tropical-wind data taken from *Naujokat and Labitzke (1993)* and *Naujokat (private communication)*. Some authors have used tropical winds near the 50 hPa level, others from the 40 – 50 hPa layer, and others near 30 hPa. Since the QBO phase determination depends on height, we take both the 50 hPa and 30 hPa as we did in *Mlch and Laštovička (1996)*. Hereinafter the symbols W-QBO and E-QBO are used for the west and east phase of QBO.

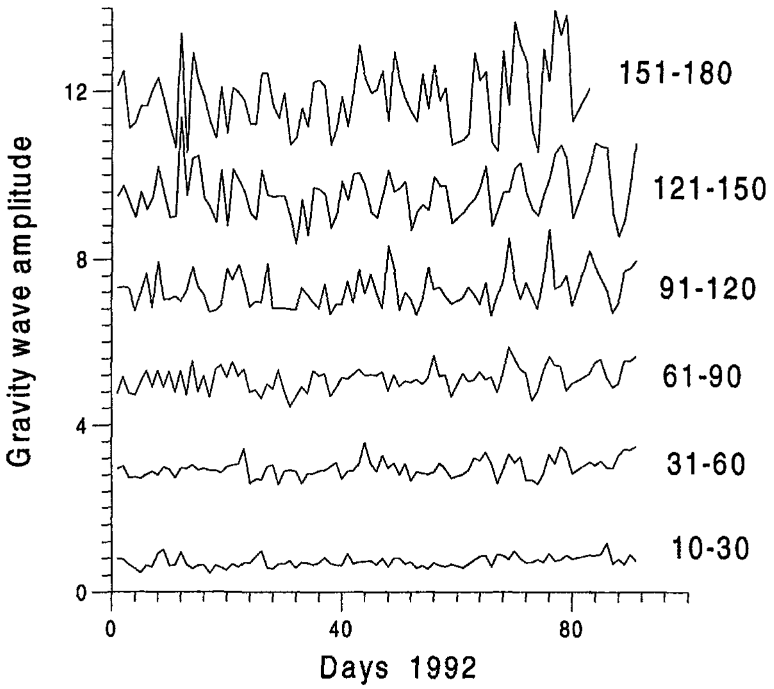

Fig. 1. Development of gravity wave activity in individual period bands 10–30, 31–60, 61–90, 91–120, 121–150, and 151–180 mins in January–March 1992. The 151–180 min band terminated on 23 March due to shorter nights. Each plot is offset by two units from the preceding one to avoid overlap. Zero level = 0 (10–30) .... 10 (151–180).

Some results on the gravity wave activity inferred from our LF absorption measurements may be found in *Laštovička et al. (1993)*, *Hauchecorne et al. (1994)*, and *Boška and Laštovička (1996)*.

3. GRAVITY WAVE ACTIVITY, QBO AND MT. PINATUBO ERUPTION

The analysis is made solely for the winter half of the year divided into two parts - October – December and January – March. In summer, information on gravity wave activity is available only for shorter periods, 10 – 90 (120) mins, with more data gaps, and without the 1994 data. Thus the results for summer appear to be less reliable and less interesting.

Figure 1 shows for January-March 1992 that there is much of day-to-day and other short-period variability in gravity wave activity. Therefore we shall use average values over periods October – December and January – March of the individual winters.

Figure 2 shows the development of gravity wave activity at shorter periods (10 – 90 min) in the winters of 1988/89 – 1994/95 (the last two winters October – – December only). Figure 3 shows the same for longer gravity wave periods (91 – 180 min). The gravity wave activity depends on the 11-year solar cycle - this effect has been studied by *Laštovička (1998)*. The possible effect of the Mt. Pinatubo volcanic eruption in June 1991 seems to be different for longer gravity wave periods (Fig. 3) as compared to shorter periods (Fig. 2). The winter just after the eruption, winter 1991/92, displays by far the highest gravity wave activity of all the winters studied for the two longest periods (121 – 150 and 151 – 180 mins). The next winter, 1992/93, displays evidently higher gravity wave activity than the two previous winters under W-QBO despite the much higher solar activity, i.e. the expected higher gravity wave activity during these two winters. Thus for the period bands 121 – 150 and 151 – 180 mins, these two winters indicate a substantial rise of gravity wave activity after the huge Mt. Pinatubo volcanic eruption. For the period bands of 61 – 90 and 91 – 120 mins the effect of the

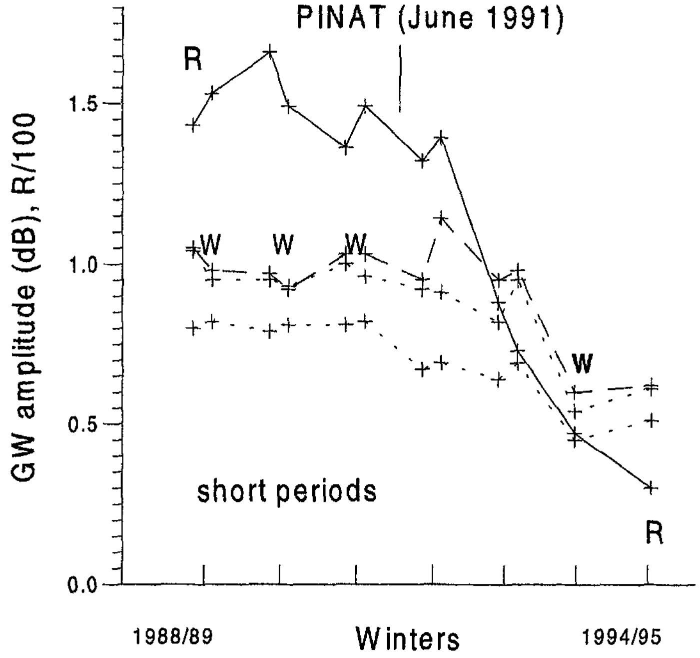

Fig. 2. Gravity wave activity in winters 1988/89–1994/95 for shorter periods - period bands 10–30 (dotted line - bottom), 31–60 (short-dashed line - middle) and 61–90 mins (long-dashed line - top). Each winter is represented by two data points - three-month averages over October– –December (first point) and January–March (second point). *R* - sunspot number (full line); short vertical line marked PINAT - Mt. Pinatubo volcanic eruption; *W* - the west phase of QBO (the other winters are in the east phase of QBO), QBO phase at 50 hPa. The last two winters (1993/94 and 1994/95) are represented only by October–December data; in the winter of 1994/95 in fact only by October–November data.

volcanic eruption seems to be much weaker but detectable and of the same qualitative pattern as for the longest periods. The shortest periods, 10 – 30 and 31 – 60 mins (Fig. 2), do not display a clearly detectable effect of the volcanic eruption. The effect of the Mt. Pinatubo eruption seems to strengthen continuously with increasing period of gravity waves. The effect was prominent in the first two winters after the eruption, 1991/92 and 1992/93, while the more recent winters displayed no clear signatures. This coincides with the recovery of the Pinatubo eruption effect in stratospheric temperatures and ozone in the winters of 1993/94 and 1994/95 (*Randel et al., 1995*).

The statistical significance of the result on volcanic eruption effects on gravity wave activity is limited by there being only one strong volcanic eruption during the interval analysed. The inaccuracy of the digital measurement itself is negligible (for the sake of gravity wave activity analysis it is not affected by inaccuracy in the determination of the zero level of absorption), much less than 1%. The predominant source of uncertainty is the large day-to-day variability (Fig. 1). The standard errors of the average values shown in Figs. 2 and 3 and the standard deviations of the respective input data were calculated for the two post-Pinatubo winters of primary interest, 1991/92 and 1992/93. The standard errors vary between 2 – 6%, being predominantly 3 – 4%. The standard deviations increase with period. They vary between 17 – 44%. For Fig. 3, the typical standard

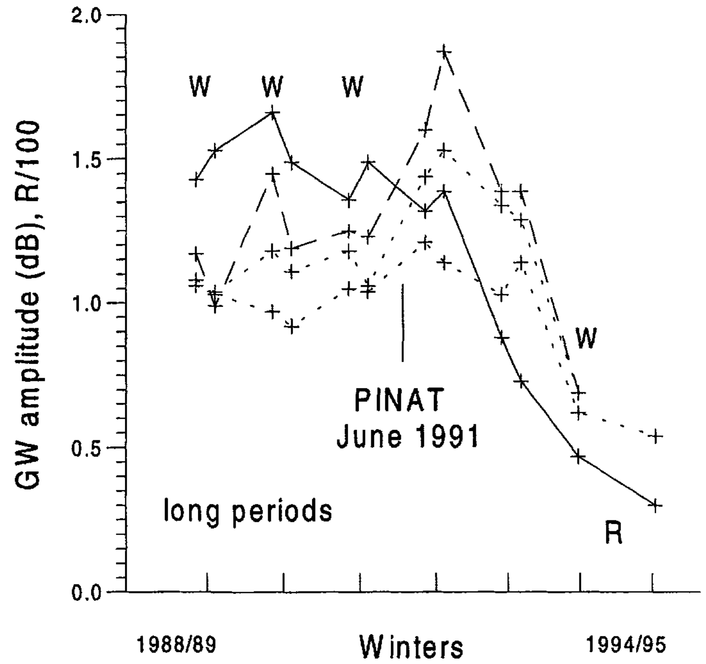

Fig. 3. The same as Fig. 2 for longer periods - period bands 91–120 (dotted line - bottom), 121–150 (short-dashed line - middle) and 151–180 mins (long-dashed line - top). The winter of 1994/95 is represented only by November data for 91–120 mins, other information could not be obtained due to too short intervals of the nighttime signal transmission.

deviation is 36%, which is comparable to the observed increase of gravity wave activity by 35 – 40% for the two longest periods. Thus, if only one subinterval (e.g. Oct – Dec 1991) displays such an increase, then it might be by chance. However, just the all four subintervals in both the post-Pinatubo winters display such a large increase of gravity wave activity (as compared to that expected from the solar activity level), but no other data set in other five winters, consequently, it is very improbable that this Pinatubo-related increase occurred only by chance.

The effect of the QBO on gravity wave activity (if any) seems to be less pronounced than that of the Mt. Pinatubo eruption. Considering only the longest (151 – 180 mins) and shortest (10 – 30 mins) periods, and taking into account solar activity (R) and the combined winter effect of QBO/solar activity on the winter stratosphere (*Labitzke and van Loon, 1988*), we may perhaps be able to trace a tendency to higher gravity wave activity under E-QBO at high solar activity and under W-QBO at low solar activity for 151 – 180 mins, and an opposite tendency for 10 – 30 mins. However, these effects are weak and statistically insignificant. No effect of the QBO is seen in Figs. 2 and 3 for other period bands. *Laštovička (1993)* found no systematic effect of QBO on planetary wave activity in the same height range and showed that a data series longer than 7 winters is needed to get a final answer.

There is another feature of gravity wave activity, namely, correlations between gravity wave activities in various period bands. *Laštovička et al. (1993)* analysed two winters and found very different correlation patterns in these winters. Table 1 shows an example of such correlations for October-December 1990. In this period, the gravity wave activity developed relatively independently in the individual period bands. The maximum correlation ($r = 0.5$) was found between the 121 – 150 and 151 – 180 min bands.

Table 2 summarizes typical correlation coefficients (0.3 in Table 1) for all the winters studied. There are winters with a good correlation between individual period bands, as 1989/90 and 1993/94, implying that gravity wave activity varies mainly in a quasi-uniform way in all period bands. On the other hand, there are winters with poor to very poor correlation between individual period bands, as 1990/91, implying that gravity wave activity does not vary uniformly, the activity in one band varying in a relatively independent manner. As for the possible dependence of the correlations on the phase of

Table 1. Matrix of correlation coefficients, all period bands (periods in minutes), October – December 1990. Number of days - 66; confidence levels: 99% for $r = 0.31$ and 95% for $r = 0.24$.

Period	10–30	31–60	61–90	91–120	121–150	151–180
10–30	1	0.3	0	0.1	0.1	0.3
31–60	0.30	1	0.3	0.2	0.3	0.3
61–90	–0.02	0.33	1	0.3	0.4	0.3
91–120	0.10	0.16	0.32	1	0.4	0.3
121–150	0.12	0.26	0.44	0.45	1	0.5
151–180	0.32	0.26	0.27	0.27	0.49	1

Table 2. Typical values of correlation coefficients between gravity wave activities in individual period bands for all winters studied. * - data based only on November 1994. QBO - phase of QBO at 50 hPa. *R* - sunspot number (Oct–Dec/Jan–Mar). QBO-30hPa - phase of QBO at 30 hPa. Confidence levels similar to those in Table 1 (except for 1994/95).

Winter	Oct.–Dec.	Jan.–Mar.	QBO	*R*	QBO–30hPa
1988/89	0.4–0.6	0.1–0.2	W	143/153	E/W
1989/90	0.7	0.7–0.9	E	166/149	E
1990/91	0.3	0.1–0.2	W	136/149	W
1991/92	0.4–0.6	0.4	E	132/139	E
1992/93	0.2–0.3	0.4–0.5	W	88/73	W
1993/94	0.7–0.8	W	47	E	
1994/95	0.4–0.5*	E	30	W	

QBO, there seems to be a tendency to better correlations under high solar activity/E-QBO and low solar activity/W-QBO conditions and vice versa. However, more data are required to confirm this tendency. The Mt. Pinatubo volcanic eruption does not seem to have any pronounced effect on correlations between gravity wave activities in individual bands.

The absorption itself contains a significant solar cycle component, the amplitude of its semiannual wave (but not the 270 kHz absorption itself) being strongly affected by the QBO (*Laštovička and Knyazev, 1990*), and absorption might be affected also by the Mt. Pinatubo eruption. To remove, or at least to suppress, the effect of these changes in absorption itself on the inferred gravity wave activity, we shall now deal with the relative amplitudes of gravity waves ($\Delta L/L$, L is absorption). On the other hand, a relatively small "new" uncertainty may be introduced due to the uncertainty in evaluating the absolute values of absorption L (= uncertainty in zero level determination).

In order to estimate the effect of the Mt. Pinatubo eruption on gravity wave activity, we use measurements of aerosol optical depth from a relatively nearby station of Geesthacht (53.4°N, 10.4°E) over the post-Pinatubo period (*Ansman et al., 1997*). For the pre-Pinatubo period, values equal to the January – March 1995 average value are taken, which may slightly overestimate or be a realistic estimate of the pre-Pinatubo level of aerosol optical depth.

Figure 4 shows the development of gravity wave activity, represented by relative amplitudes (3-month average gravity wave activity divided by 3-month average absorption), in all six period bands. The considerable increase in gravity wave activity in the two longest-period bands during the two post-Pinatubo winters, compared to the levels expected on the basis of solar activity, remains to occur and coincides with the aerosol optical depth increase. The gravity wave activity in all period bands again generally does not show an evident dependence on the phase of QBO as in Figs. 2 and 3.

In order to estimate the effect of the Mt. Pinatubo eruption quantitatively, a simple two-parameter linear regression is computed:

$$GW\text{amplitude} = A \text{ Sunspots} + B \text{ Aerosols} + C \qquad (1)$$

The values of A, B and C for the two longest-period bands, which appear to be affected by the Mt. Pinatubo eruption more than other period bands (Fig. 4), are shown in Table 3.

Figure 4 also shows that the 3-month average amplitudes of gravity waves vary between about 2 – 8% of the absolute magnitude of absorption. Due to the large day-to-day variability, the gravity wave amplitudes may be well above 10% on individual days.

The volcanic effect is largest for the 151 – 180 min band (Fig. 4). According to Eq.(1) and Table 3, the effect of volcanic activity attains its maximum during studied winters 1988/89 – 1993/94 in January – March 1992, when it contributes 3.4% to the gravity wave amplitude of 8.3%, which is quite a significant contribution. This effect is larger than the effect of the difference between the maximum ($R = 166$) and minimum ($R = 47$) three-month levels of solar activity in the winters studied, which produces a difference of 2.8%.

All the above results on the QBO phase effect on gravity wave activity are based on the QBO phase taken at the 50 hPa level. If we determine the QBO phase from the 30 hPa level winds, the QBO phase becomes mixed E/W for the first winter, is the same as QBO

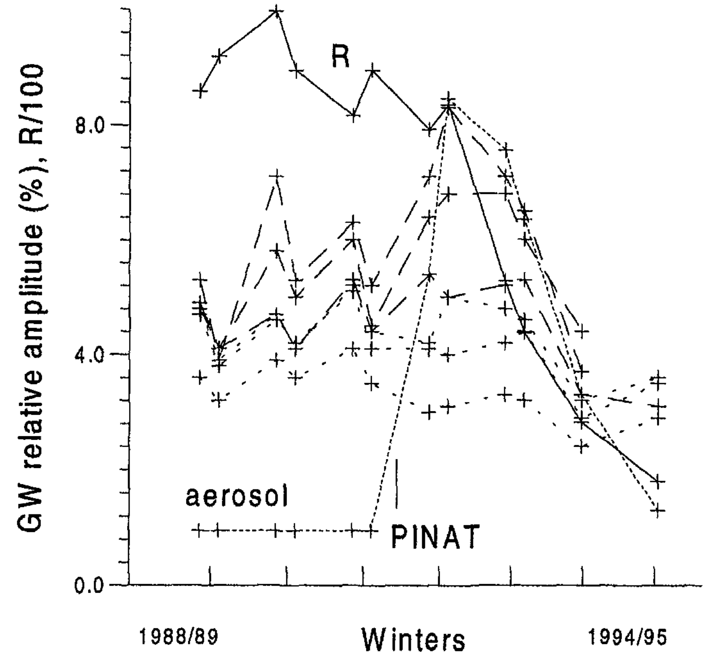

Fig. 4. The gravity wave activity represented by relative amplitudes for all period bands - 10–30 min (dashed line - bottom) to 151–180 mins (longest-dash line - top) - in winters 1988/89–1994/95. R - sunspot number (full line); aerosol – quasi-local aerosol optical depth (short-dash line); short vertical line marked PINAT - Mt. Pinatubo volcanic eruption. The last two winters, 1993/94 and 1994/95, are represented only by October–December and October–November, respectively.

Table 3. Parameters of Eq.(1) computed for relative amplitudes of the 121–150 and 151–180 min period bands on the basis of 3-month average values as used in Fig. 4. Std. err.- standard error, sig. lev. - level of significance. R^2 shows how much of the total variance is described by Eq.(1).

Band	A			B			C			R^2
[min]	value	std. err.	sig. lev.	value	std. err.	sig. lev.	value	std. err.	sig. lev.	
120-150	0.0097	0.0061	0.152	15.03	3.84	0.005	3.31	0.94	0.008	0.66
150-180	0.0240	0.0080	0.020	22.40	5.26	0.003	1.46	1.28	0.290	0.70

at 50 hPa for the second to fifth winters, and becomes opposite to that of QBO at 50 hPa for the last two winters. The QBO effect appears to differ from that for the 50 hPa QBO. Table 2 shows that for the 30 hPa QBO, the correlations between the gravity wave activities in the different period bands are systematically better for E-QBO. All three E-QBO winters display better correlations than W-QBO winters (with a partial exception of the Mt. Pinatubo winter of 1991/1992). Nevertheless, the level of gravity wave activity after replacing the phases of QBO in Figs. 2, 3 and 4 with those from Table 2 for 30 hPa (opposite phase in the last two winters) again displays no evident influence of the QBO phase.

The observed difference between the effects of the 50 hPa and 30 hPa QBO is not surprising. There is a phase advance of several months between the 30 hPa QBO and the 50 hPa QBO. W-QBO prevails (lasts longer) at 50 hPa, and E-QBO at 30 hPa.

The effects of QBO (if any) have not been established with sufficient reliability. More investigations are necessary before we can begin to consider possible mechanisms.

The Mt. Pinatubo eruption, the strongest "stratospheric" volcanic eruption of the 20th century, had strong effects on the troposphere and stratosphere (at least the lower stratosphere), hence the existence of its effect on gravity wave activity is not surprising. The observed effect occurred just when it should have occurred, in the first two winters after the Mt. Pinatubo eruption. We expect changes in tropospheric gravity wave activity/sources to play a role. Cold fronts, cyclones and storms belong to the most important tropospheric sources of gravity waves. Storm tracks in the North-Eastern Atlantic ($\varphi > 50°$N, $\lambda = 20°$W – 10°E) in winter (December – February) are, on the average, shifted by 2.5° southward from the solar cycle minimum to the solar cycle maximum, as shown by *Brown and John (1979)*. Circulation and, thus, storm tracks are expected to be affected by strong volcanic eruptions. Changes in the filtering properties of the middle atmosphere are also expected to play a role. The (lower) stratosphere was warmer for 1 – 2 years at low latitudes, while a delayed cooling (consequence of ozone reduction) was more pronounced at higher latitudes (*Randel et al., 1995*). This results in stronger differential heating, which should strengthen zonal circulation with consequences to planetary and partly gravity wave upward propagation. As far as we know, possible changes of the mesosphere after volcanic eruptions have not been studied. They could affect the conditions of gravity wave breaking and energy dissipation in the mesosphere below radio wave absorption altitudes (90 – 95 km). The atmospheric changes after strong volcanic eruptions, particularly changes of circulation, are not known sufficiently to allow a reliable scenario/mechanism of the Mt. Pinatubo eruption effect on the gravity wave activity to be proposed.

4. CONCLUSION

Exploiting all available information on gravity wave activity, inferred from the nighttime A3 radio wave absorption measurements in the lower ionosphere over central Europe, we can draw the following conclusions concerning gravity wave activity in the winter half of the year (October – March):

(1) There was a substantial enhancement of the long-period (2 – 3 hours) gravity wave activity in the two winters just after the strong volcanic eruption of Mt. Pinatubo. For the shortest periods, 10 – 30 and 31 – 60 mins, no distinct enhancement of gravity wave activity was observed; in particular the 10 – 30 min band exhibits no enhancement at all.

(2) There seems to be no evident effect of the phase of QBO on the level of gravity wave activity. On the other hand, available data provide an indication of a possible effect of QBO on the correlations between gravity wave activities in individual period bands. However, results based on the 50 hPa QBO phase and the 30 hPa QBO phase differ qualitatively in the effect on correlations. To establish reliably the effect of QBO on gravity wave activity (if there is any) requires a longer data series which, unfortunately, is not available.

The above results are based solely on measurements along one radio path at 270 kHz (nobody has used other radio wave absorption data to infer gravity wave activity) and they describe the situation in Central Europe at night. Some of them are preliminary due to too short data series available. Unfortunately, since 1995 the 270 kHz transmitter has been working in a regime which makes use of these measurements for gravity wave activity monitoring impossible. Currently, we are searching for another suitable LF transmitter in Central Europe in order to be able to continue ionospheric measurements, analyses and gravity wave activity studies.

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