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Impact of the Mt. Pinatubo volcanic eruption on the lower ionosphere and atmospheric waves over Central Europe

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Abstract
The very strong volcanic eruption of Mt. Pinatubo in June 1991 directly affected the troposphere and lower and middle stratosphere. Here we look at its effects in the mesopause region as revealed by the radio wave absorption measurements in the lower ionosphere over Central Europe and inferred planetary and gravity wave activity. The gravity wave activity inferred from the nighttime LF radio wave absorption displays an evident enhancement for waves of periods of about 2-3 h coinciding with regional measurements of the optical depth of (volcanic) aerosols, while there is no detectable effect for short period waves ($T < 1$ h). There is no detectable effect in the planetary wave activity inferred from the daytime HF radio wave absorption. As for the absorption itself, the results on the impact of the Mt. Pinatubo eruption do not provide an observable effect.

Key words *volcanic eruption – lower ionosphere – atmospheric waves – radio wave absorption*

1. Introduction

The Mt. Pinatubo volcano erupted in June 1991. This eruption was accompanied by the largest injection of volcanic aerosols into the stratosphere observed in the 20th century. The cloud of erupted aerosols reached altitudes around 30 km. After the Mt. Pinatubo eruption the stratosphere warmed due to the absorption of radiation by the new aerosols produced by the eruption, particularly at low latitudes (*e.g.*, Labitzke, 1994). The absorbed radiation was missing in the troposphere and, therefore, the troposphere cooled. At middle and higher latitudes, the enhanced concentration of volcanic aerosols resulted (with some delay) in a reduction of ozone concentration in the (lower) stratosphere (*e.g.*, McGee *et al.*, 1994). Some 1-2 years after the eruption the ozone reduction-related cooling overwhelmed the original aerosol heating and a mild cooling of the stratosphere appeared (*e.g.*, Randell *et al.*, 1995).

The pronounced volcano-related changes in the troposphere and stratosphere allow us assume the possibility of changes in the lower ionosphere due to:

– Changes in tropospheric sources of upward propagating waves (gravity and planetary).

– Changes in filtering properties of the stratosphere to the upward propagating waves.

Here such possible changes in the lower ionosphere are studied with the use of radio wave absorption measurements (monitoring) in the lower ionosphere over Central Europe. Possible effects on gravity and planetary wave activity inferred from absorption measurements and on absorption itself are investigated. The existence of the effect of Mt. Pinatubo on the gravity wave activity inferred from absorption was demonstrated by Laštovička *et al.* (1998).

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Section 2 describes data and methods. Section 3 illustrates effects in gravity wave activity. Section 4 deals with possible effects in planetary wave activity and Section 5 in the absorption itself. The paper ends with brief conclusions.

2. Data and methods

The radio wave absorption in the lower ionosphere was measured by the A3 method, which consists in receiving a continuous sky wave transmitted usually by a commercial transmitter with an oblique incidence on the ionosphere. The A3 method exists in two versions, Low Frequency (LF) version and Medium/High Frequency (MF/HF) version, which differ by the method of calibration and by antenna systems. The LF version in digital modification used by us was described by Laštovička *et al.* (1993). The HF A3 measurements used in the paper were described by Laštovička and Jiskra (1978) in the older analog version, which was operating till the early 1990s.

The LF absorption was measured at Pruhonice on 270 kHz (reflection point 49.45°N, 16.05°E; transmitter-receiver distance 236 km; nighttime reflection height ~ 95 km). The gravity wave activity (in terms of average gravity wave amplitude) was inferred from well nighttime data ($\chi > 100^{\circ}$) by the correloperiodogram method applied to each individual night (for details see Laštovička *et al.*, 1993). The well-nighttime data are used to exclude the effect of strong daytime variation of reflection height, *i.e.* of substantial changes in the height region where the absorption is created, on the derived gravity wave activity. Moreover, well in daytime there is no measurable signal on the given frequency due to total absorption.

The HF absorption was measured at Panska Ves on 6090 kHz (reflection point 50.07°N, 10.30°E; transmitter-receiver distance 610 km; daytime reflection height ~ 97-98 km). Daytime absorption data at solar zenith angle $\chi = 75^{\circ}$ (average from morning and afternoon data) are used for inferring the planetary wave activity (in terms of average planetary wave amplitude) from consecutive 2 month planetary wave oscillation spectra by the correloperiodogram method (for details see, *e.g.*, Pancheva *et al.*, 1989). At night and high solar zenith angles close to sunrise and sunset, radio waves for this radio path are reflected in the *F* region, *i.e.* we cannot measure a pure absorption in the lower ionosphere. Therefore, only well-daytime data may be used.

The aerosol optical depth is considered as a measure of volcanic aerosols. We use data measured at relatively nearby station Geesthacht, Germany, 53.4°N, 10.4°E (Ansman *et al.*, 1997). They published data for August 1991-March 1995. The pre-Pinatubo level of aerosols was taken to be equal to the essentially undisturbed level of January-March 1995. A possible error in estimating the pre-Pinatubo level does not play a role with respect to the large Pinatubo-related increase of concentration of volcanic aerosols in the stratosphere, which peaked at Geesthacht in 1992 and winter/early spring 1993 (see fig. 1).

3. Gravity waves

The effect of the Mt. Pinatubo volcanic eruption on the gravity wave activity was studied in Central Europe based on the nighttime absorption at 270 kHz by Laštovička *et al.* (1998) and Laštovička (1999). Figure 1 shows the development of gravity wave activity in six period ranges between 10-180 min in the winter half of the year (October-March) for winters 1988/1989-1994/1995 (the last two winters October-December only). The measurements became unreliable after 1 January 1995 due to changes of transmitter regime. They were terminated a couple of years ago. All available wintertime data are shown in fig. 1.

An evident increase in gravity wave activity after the Mt. Pinatubo eruption is revealed at long periods ($T > 120$ min, top curves) in very good coincidence with the large increase in the volcanic aerosol optical depth. This increase in gravity wave activity is well pronounced despite the decreasing solar activity (Laštovička (1999) found an increase in gravity wave activity with increasing solar activity). However, no detectable Pinatubo-related change of the gravity wave activity at short periods ($T < 60$ min, bottom curves) can be observed.

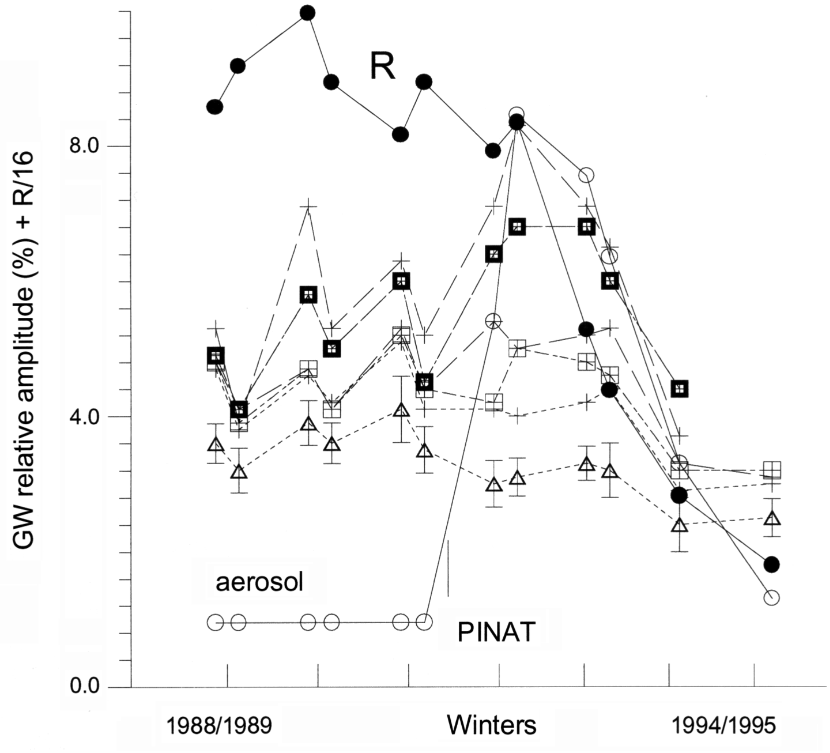

Fig. 1. Gravity wave activity (relative amplitude in %) inferred from the nighttime 270 kHz absorption measured in Central Europe, winters of 1988/1989-1994/1995 (after Laštovička, 1999). *R* - sunspot number. Winter data points – October-December and January-March averages. Gravity wave periods (from bottom to top of the figure): Δ for 10-30 min, + for 31-60 min, □ for 61-90 min, + for 91-120 min, ■ for 121-150 min, + for 151-180 min.

What might be the origin of the longer-period (2-3 h) gravity wave activity response to the Mt. Pinatubo eruption? The seasonal variation pattern of the gravity wave activity and its change with altitude in the middle atmosphere is significantly affected by the background wind and temperature fields, which affect propagation and dissipation of gravity waves (*e.g.*, Gavrilov and Fukao, 1999). On the other hand, the solar cycle dependence of the seasonal variation pattern of the gravity wave activity inferred from the 270 kHz nighttime radio wave absorption measurements seems to be substantially affected by a shift of the average storm tracks in the Northern Atlantic region, *i.e.* by changes in the gravity wave source (Bošková and Laštovička, 2001). Background temperature fields in the troposphere and stratosphere were affected by the Mt. Pinatubo eruption. As concerns other parameters, sufficient information is not available. Nevertheless, some changes in the wind field and maybe tropospheric storm tracks can be expected, which would mean that both the changes in gravity wave sources and filtering properties of the stratosphere could play a role. However, it is not clear at all why the longer period gravity waves are affected, whereas this is not the case for the short period gravity waves.

Unfortunately, the available data do not enable us to analyze effect of another strong volcanic eruption, that of El Chichon in 1982. As far as I know, the impact of volcanic eruptions on the gravity wave activity in the upper mesopause region has not been studied by any other author.

4. Planetary waves

The daytime 6090 kHz absorption is used to investigate the potential effect of the Mt. Pinatubo eruption on the planetary wave activity in the lower ionosphere in Central Europe. Figure 2 displays the development of the planetary wave activity for the period 1971-1996. Each data point is taken from a spectrum computed from a two-month interval.

We do not see any observable effect of the Mt. Pinatubo volcanic eruption on the planetary wave activity as deduced from daytime radio wave absorption in Central Europe. In the 1990s, the only evident change is a decreasing variability of the planetary wave activity towards the end of the period. On the other hand, the planetary wave activity is very noisy, so a small effect of Pinatubo would be undetectable. Nevertheless such a clear effect like that in the gravity wave activity evidently has not been observed. If the main reason of the effect of Pinatubo in the gravity wave activity is a shift in storm tracks, then we should expect rather no effect of Pinatubo on the planetary wave activity, which is not affected significantly by shifts of storm tracks.

5. Radio wave absorption

The 270 kHz measurements are reliable till the end of 1993. Since January 1994 they are

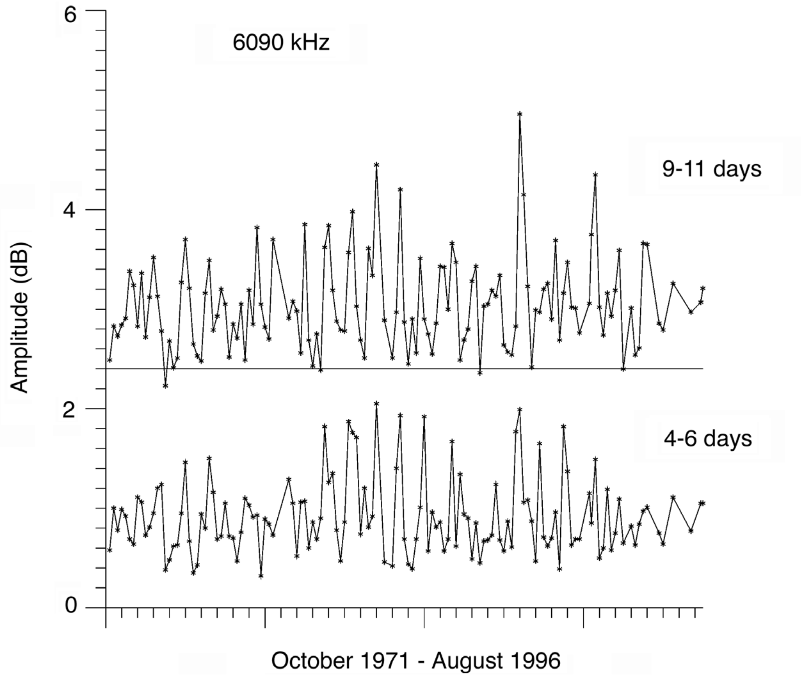

Fig. 2. Planetary wave activity (amplitude) inferred from the daytime 6090 kHz radio wave absorption measured in Central Europe at the solar zenith angle of 75°, October 1971-August 1996.

Table I. Matrix of correlation coefficients.

	Aerosol	Sunspot	aa	Absorption
Aerosol	1	**0.61**	0.09	0.07
Sunspot	**0.61**	1	0.35	**0.51**
aa	0.09	0.35	1	0.19
Absorption	0.07	**0.51**	0.19	1

Table II. Matrix of partial correlation coefficients.

	Aerosol	Sunspot	aa	Absorption
Aerosol	1	**0.68**	– 0.18	– 0.36
Sunspot	**0.68**	1	0.33	**0.57**
aa	– 0.18	0.33	1	– 0.04
Absorption	– 0.36	**0.57**	– 0.04	1

Table III. Principal component analysis ($f1+f2+$ $+f3=95\%$).

Factor	$f1$	$f2$	$f3$
%	50%	25%	20%
Aerosol	**0.67**	**– 0.69**	– 0.12
Sunspot	**0.93**	– 0.11	0.06
aa	**0.51**	**0.52**	**– 0.67**
Absorption	**0.63**	0.48	**0.58**

Table IV. Varimax rotated principal component analysis.

Factor	$f1$	$f2$	$f3$	$f4$
Aerosol	**0.96**	0	0.02	0.26
Sunspot	0.40	0.32	0.20	**0.83**
aa	– 0.04	0.08	**0.99**	0.13
Absorption	0.01	**0.97**	0.08	0.21

mostly unreliable due to transmitter problems except for a few months (fortunately those allowing construct fig. 1). Therefore only the 6090 kHz data are used to examine the effect of the Mt. Pinatubo eruption in radio wave absorption itself. To find the possible effect, matrices of correlation coefficients and partial correlation coefficients are computed and the principal component analysis without and with rotated axes is applied. Monthly mean values of the aerosol optical depth, sunspot number (solar activity), aa index (geomagnetic activity) and absorption are used. The results are presented in tables I-IV.

Tables I and II show that neither correlation coefficients, nor partial correlation coefficients reveal an effect of the Mt. Pinatubo eruption on radio wave absorption. The correlations point to the well-known positive relation between absorption and solar activity (via changes of intensity of ionizing radiation). The correlation between volcanic aerosol and sunspots is accidental due to the occurrence of aerosol recovery at the decay branch of the solar cycle.

Neither standard (table III), nor rotated (table IV) principal component analysis provides an effect of Mt. Pinatubo eruption on radio wave absorption. This corresponds to the results based on correlations shown in tables I and II. Table IV again points to some relation between absorption and solar activity (sunspots) and displays the above-explained accidental correlation of aerosol and sunspot cycle. Thus we can say that there is no observable effect of the Mt. Pinatubo volcanic aerosols on daytime radio wave absorption in the lower ionosphere above about 90 km.

6. Conclusions

All conclusions are based on the radio wave absorption measurements in the lower ionosphere over central Europe.

i) No observable effects of the Mt. Pinatubo volcanic eruption were found in the daytime HF radio wave absorption itself and in the planetary wave activity inferred from this absorption.

ii) In the gravity wave activity derived from the nighttime LF radio wave absorption, no effect of Mt. Pinatubo was found for short-period gravity waves ($T < 1$ h). However, a substantial intensification of the longer-period gravity wave activity ($T = 2$-3 h) was observed.

iii) The origin of the gravity wave activity enhancement may be due to both changes in properties of the middle atmosphere and in gravity wave sources. The real origin of this enhancement and an answer to the question while only longer-period gravity waves are enhanced is not clear at present and will be the subject of further investigations.

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