GRAVITY WAVE ACTIVITY IN THE MIDDLE STRATOSPHERE DURING WINTER AS OBSERVED BY THE ALOMAR O_3-LIDAR AND THE BONN UNIVERSITY LIDAR AT ESRANGE IN NORTHERN SCANDINAVIA

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ABSTRACT

Buoyancy waves appear regularly in the polar winter stratosphere. In particular the existence of polar stratospheric clouds in the Arctic is closely connected to the occurrence of orographically induced gravity waves. Such waves modulate atmospheric temperature profiles which are measured in the middle atmosphere by the Alomar O_3-lidar in northern Norway and the Bonn University lidar at Esrange in northern Sweden. Both experiments have been operated for several years resulting in a comprehensive data base. We have analysed these data from several winters with respect to atmospheric gravity waves. The gravity wave potential energy density is a measure for the wave activity and it can be derived from the lidar data. Interestingly the gravity wave activity at Alomar is on average at least as strong as that above Esrange. It varies from year to year but is also different for different months. The differences of gravity wave activity between Alomar and Esrange is strongest from December to February. Finally, a strong dependence of gravity wave activity on the ground wind direction is observed at Alomar while the distribution is more independent at Esrange.

Key words: Gravity waves, stratosphere, temperature.

1. INTRODUCTION

Atmospheric buoyancy or gravity waves have a large impact on the polar atmosphere. During summer these waves modify the mesospheric circulation and lead to cold polar mesopause temperatures of 150 K or colder (e.g., Lindzen, 1982; Fritts, 1984). During winter gravity waves are crucial for the formation of polar stratospheric clouds in the Arctic (e.g., Volkert and Intes, 1992; Blum et al., 2005). Gravity waves can be excited orographically and propagate from the ground through the troposphere into the stratosphere and higher, as long as favourable propagation conditions exist (Scorer, 1949). For the excitation of orographically induced gravity waves Dörnbrack et al. (2002) determined a minimum required ground wind speed of 5 – 10 m/s. Wind shears in the troposphere or middle atmosphere create critical levels which lead to dissipation of vertically ascending gravity waves (e.g., Fritts and Alexander, 2003, and references therein). In particular major stratospheric warmings lead to a reversed circulation in the stratosphere (Matsuno, 1971) and thus create critical levels for atmospheric gravity waves (e.g., Blum et al., 2006).
Atmospheric gravity wave signatures are often found in temperature profiles. The Alomar O_3-lidar (69°N, 16°E) in northern Norway (Hoppe et al., 1995) as well as the U. Bonn lidar at Esrange (68°N, 21°E) in northern Sweden (Blum and Fricke, 2005) have been operated for several years and thus a comprehensive data base exists. We have retrieved temperature profiles from the lidar measurements and analysed them with respect to gravity wave signatures.
First we will describe the instrumentation and the available data sets as well as the method to analyse gravity wave signatures in temperature profiles derived from lidar measurements. Then we will present and discuss the observations obtained from the analysis. Finally the results are summarised.

2. INSTRUMENTATION, DATA SET, AND ANALYSIS METHOD

The Alomar O_3-lidar is a differential absorption lidar (DIAL) which operates at the two wavelengths 308 nm and 353 nm. The lidar utilises a XeCl excimer laser with 200 Hz repetition rate. The backscattered light is collected by a Newtonian telescope with a primary mirror of 1 m diameter. The collected light is detected by photomultipliers and counted with an altitude resolution of 100 m. Actively stabilised Fabry-Perot Etalons allow measurements during daylight. To cover a large altitude range from the lower troposphere to the stratopause, a special measurement mode is applied. For each measurement run of about five minutes time a different neutral density filter is inserted into the optical bench to change the intensity of the backscattered light which falls on the detectors. The delay of the mechanical chopper is adjusted accordingly to block a different altitude range of the atmospheric profile. Three different configurations for neutral density filters (ND) and chopper edges (z) are used: (1) ND = 0, z $\approx$ 18 km (2) ND = 1, z $\approx$ 12 km (3) ND = 2, z $\approx$ 7 km. The ND-number is the base 10 logarithm of the filter attenuation. The Alomar O_3-lidar has been operated regularly during summer (i.e. in daylight) as well as during winter since 1994 whenever weather permitted measurements.
The Bonn University lidar at Esrange is a Rayleigh/Mie/Raman lidar and it uses a Nd:YAG

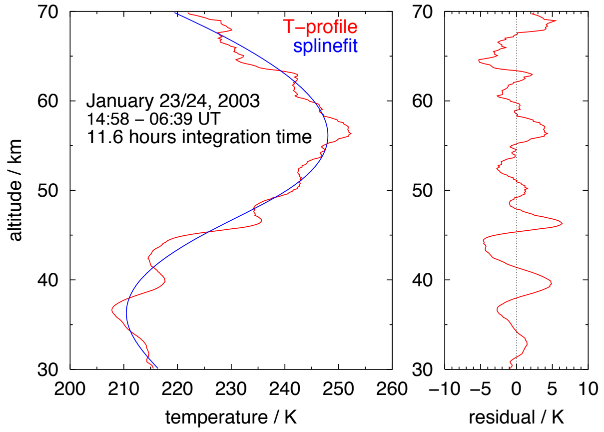

Figure 1. The left panel shows the temperature profile as observed by the U. Bonn lidar at Esrange (red line) and the accompanying spline fit (blue line) on 23/24 January 2003. The integration time was almost 12 hours. In the right panel the residual of the measured profile w.r.t. the spline fit is shown.

laser as light source which emits linearly polarised light with a repetition rate of 20 Hz at a wavelength of 532 nm. Three bore-sighted Newtonian telescopes with a diameter of 50 cm each are used for detection. The altitude resolution of the U. Bonn lidar is 150 m. Density-tuned fixed spacer etalons in combination with narrowband interference filters allow for daylight measurements. To cover a wide altitude range from 5 – 100 km the lidar uses an intensity cascaded chain of detectors. The U. Bonn lidar was set up at Esrange in December 1996 and measurements started in January 1997. The lidar is operated on a campaign basis, about 4 – 6 weeks each summer and winter.

The detected signal from each lidar is directly proportional to the molecular number density in the aerosol-free part of the atmosphere (i.e. above 30 km altitude). Assuming hydrostatic equilibrium, the integration of the range corrected lidar net signal yields the temperature profile (Kent and Wright, 1970; Hauchecorne and Chanin, 1980). At the upper end of the profile a seed temperature is needed which we take from the MSISE90 model (Hedin, 1991).

For each day the measurements in the same (ND,z)-configuration of the Alomar lidar at 353 nm wavelength have been used to calculate a temperature profile. The integration time of the different temperature profiles varies from 15 min to 75 min. Measurement runs at Esrange normally last longer than measurements at Alomar. Here, lidar data were integrated for 1 h with a shift in the starting point of 15 min as previously done by Blum et al. (2004).

To determine the undisturbed background temperature profile we fit a smoothing cubic spline to the individual temperature profiles. The residual between the measured profile and the spline fit describes the wave perturbation as shown in Fig. 1. At about 45 km altitude the wave amplitude decreases and the shape changes, too. This can be attributed to changing meteorological conditions and thus different atmospheric transparencies for vertically propagating gravity waves. While in the middle stratosphere ($\sim$ 20 – 40 km) there was a strong jet from northwest, the wind speed decreased in the upper stratosphere (> 40 km) and the wind direction turned to southwest.

The temperature residuals are used to calculate the gravity wave potential energy density per volume $GWPED_{vol}$, which is given by

$$GWPED_{vol} = \frac{1}{2}\frac{g^2(z)}{N^2(z)}\overline{\left(\frac{\Delta T(z)}{\overline{T(z)}}\right)^2}\, n(z)\,\overline{m}. \qquad (1)$$

This quantity consist mainly of the mean of the squared relative temperature variation $\overline{(\Delta T(z))/(\overline{T(z)})^2}$ where $\Delta T(z)$ is the temperature perturbation described by the residual and $\overline{T(z)}$ is the undisturbed temperature profile represented by the spline fit. The relative temperature perturbation is further multiplied by a stability factor which consists of the acceleration due to gravity $g(z)$ and the Brunt-Väisälä frequency $N(z)$. The symbol $n(z)$ stands for the molecular number density which is taken from the lidar measurement. Finally $\overline{m}$ is the mean molecular mass of the atmosphere. The $GWPED_{vol}$ is a measure for the potential energy available in an observed gravity wave and is used to determine the wave activity. We will use the average $GWPED_{vol}$ in the altitude range from 30 – 40 km. Since the influence of the seed value at the top of the temperature profile reduces exponentially with decreasing altitude, temperature profiles are only used when the top altitude is higher than 55 km.

3. OBSERVATIONS AND DISCUSSIONS

Fig. 2 shows the mean $GWPED_{vol}$ in the altitude range form 30 – 40 km for different winters. Here winter is defined to mean the months November to March. The average wave activity at Esrange is lower than that at Alomar, although Esrange is normally during winter on the lee-side of the Scandinavian mountains, which are an orographic source of gravity waves. Large variability dur-

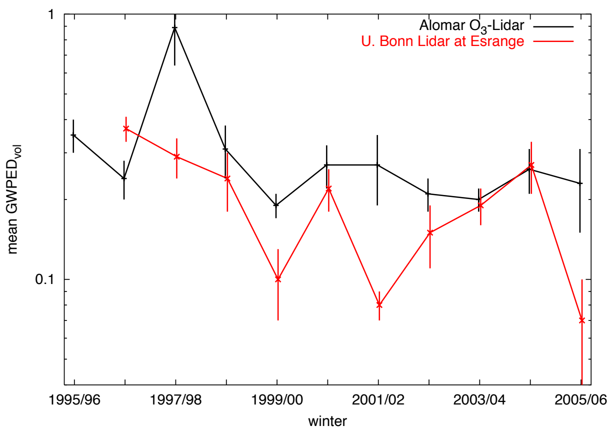

Figure 2. Mean $GWPED_{vol}$ and error of mean in the middle stratosphere (30 – 40 km) as measured by the Alomar O_3-lidar (black line) and the U. Bonn lidar at Esrange (red line) during winter, i.e. November to March.

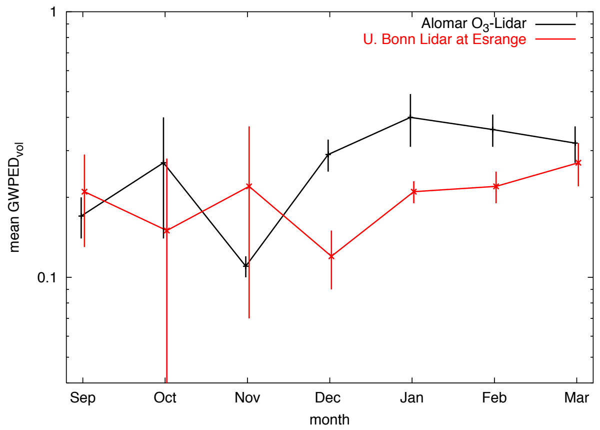

Figure 3. Same as Fig. 2, but for different months, averaged over several years.

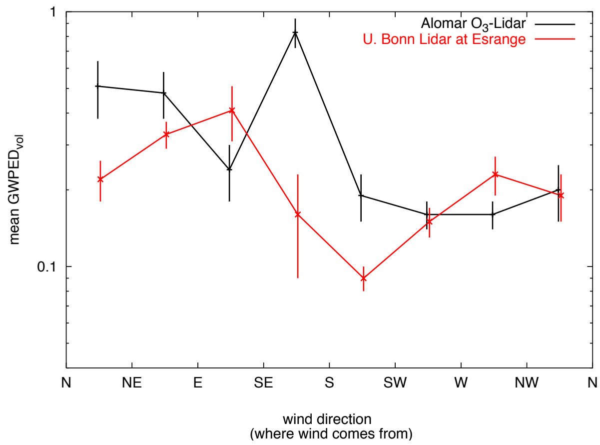

Figure 4. Same as Fig. 2, but for direction of ground wind as given in ECMWF T106 model.

ing the different years can be found on both sides of the mountains. While the Alomar data cover the complete winter period limited only by weather, the distribution of the Esrange data during the respective winters depends on the campaign times. Thus, e.g., stratospheric warmings can have influenced observed gravity wave activity at Esrange during one winter if the campaign covered only the period close to such a warming.

The smaller $GWPED_{vol}$ during winter 2001/02 at Esrange might be due to a major stratospheric warming in December 2001 (Naujokat et al., 2002). During this winter the Esrange lidar was operated from beginning of December to mid-February and thus covers most of the winter. The major warmings in January 2003 (Naujokat and Grunow, 2003) and January 2004 (Labitzke et al., 2005) have obviously not influenced the wave activity at either station. During winter 2005/06 measurements at Esrange were restricted to the first three weeks of January. During this time a stratospheric warming was observed which probably reduced the wave activity during the campaign time.

In Fig. 3 the mean $GWPED_{vol}$ in the altitude range from 30 to 40 km is shown for different months averaged over several years. From September to November the gravity wave activity at Alomar and at Esrange is about the same. But during the winter core-months from December to February the gravity wave potential energy density at Alomar is higher than that at Esrange, in particular during December. At the end of the winter the $GWPED_{vol}$ at both stations becomes similar again. During all the months the $GWPED_{vol}$ at Esrange stays quite constant with a slight increase towards the end of the winter. Apparently the excitation and propagation conditions for orographically induced gravity waves are similar during this period. This is different at Alomar. There is a clear difference between the $GWPED_{vol}$ during September to November and December to March. Since both stations are only about 250 km apart, we may assume that the propagation conditions for gravity waves above both stations are similar. However, the excitation conditions may vary.

Orographically induced gravity waves depend on the direction and strength of the ground wind. The direction is important, because the orography differs with direction. Alomar is located on the Norwegian island Andøya; north and west of Alomar there is the Atlantic Ocean but no orography to excite buoyancy waves. However, south and southeast of Alomar there are the Lofoten islands with mountains up to 1000 m altitude. On the other hand, Esrange is located in a hilly region which shows small hills of low altitude all around. About 150 km west of Esrange the Scandinavian mountain range rises with mountains as high as 2000 m. The sources of gravity waves are spatially more homogeneously distributed for Esrange than for Alomar.

Fig. 4 shows the mean $GWPED_{vol}$ in the altitude range from 30 to 40 km averaged over all data from September to March in dependence of the wind direction. The wind direction is taken from the lowest level of the ECMWF T106 analysis at Alomar and Esrange. At Esrange the gravity wave potential energy density is low for winds from south to southwest, while winds from other directions produce a stronger wave activity. At Alomar this is completely different. Winds from the south to southeast produce very strong waves with $GWPED_{vol}$ values which are about 5 times larger than that from western directions. Also winds from the north or northeast excite strong gravity waves above Alomar. When the wind comes from the ocean, the wave activity is much smaller. Obviously the wave activity at Alomar depends crucially on the wind direction according to the inhomogeneous orography while the wave excitation at Esrange is relatively independent of wind direction in the troposphere which agrees well with the more homogenous orography in northern Sweden.

4. SUMMARY AND OUTLOOK

The gravity wave activity at the two stations Alomar and Esrange in northern Scandinavia was analysed based on temperature oscillations in lidar profiles. The gravity wave potential energy density per volume ($GWPED_{vol}$) was compared and showed similar values at both stations throughout the different winters. Differences at both stations are most probably due to different measurement periods caused by different weather conditions and campaign-based measurements only at Esrange.

While the gravity wave activity is very similar from Sep-

tember to March at Esrange with a slight increase to the end of the winter, the $GWPED_{vol}$ at Alomar depends heavily on the time of the year. During winter it is twice as large as during autumn. Also the wind direction is at Alomar more important for gravity wave excitation than at Esrange. This reflects the different spatial distribution of gravity wave sources (= mountains) about both stations.
Since gravity waves have been observed to be central for polar stratospheric cloud formation at Esrange the comparison raises the question about the occurrence frequency of PSC at Alomar, which is lower than at Esrange. Large gravity wave activity causes modulations of the temperature profile and should lead to the formation of PSC if the undisturbed background temperature is sufficiently close to the PSC formation temperature threshold. Additional analyses are needed to combine the gravity wave analysis with the PSC observations and the meteorological background situation not only near the ground but also in the troposphere and stratosphere with respect to the polar vortex.

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