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Long-term trends and decadal variability of upper mesosphere/lower thermosphere gravity waves at midlatitudes

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ABSTRACT

Mesosphere/lower thermosphere (MLT) winds over Germany as measured with a low-frequency spaced receiver system at Collm 1984–2007 have been analysed with respect to variations at the time scales of gravity waves. Background winds are also registered to analyse possible gravity wave-mean flow interactions at decadal and interdecadal time scales. In both winter and summer an increasing mesospheric zonal wind jet with time is registered, which is accompanied with increasing gravity wave variances. At greater altitudes in summer, the mean wind jet trend reverses, and negative trends of gravity wave variances are found. This connection between gravity waves and mean wind is also observed on a quasi-decadal scale: during solar maximum stronger mesospheric zonal wind jets as well as larger gravity wave amplitudes are observed. This results in a solar cycle modulation of gravity waves with larger amplitudes during solar maximum. The observed positive correlation between gravity wave amplitudes and the mean zonal wind may follow the theory of saturated waves in the atmosphere, such that stronger mesospheric zonal winds are connected with larger gravity wave amplitudes.

1. Introduction

Gravity waves (GWs) play a crucial role in the dynamics of the mesosphere/lower thermosphere (MLT) region. Their sources are mainly located in the troposphere, and they transport energy and momentum to the middle atmosphere, thus leading to a coupling between atmospheric layers. Changes of GW parameters and amplitudes are thus connected with changes in atmospheric coupling, and the analysis of interannual changes and long-term trends of GW may give insight into changes of the atmosphere as a whole. Acceleration of the mean flow through GWs mainly occurs in the mesosphere/lower thermosphere (MLT). This region is characterised by the zonal wind reversal, i.e. the change of the mesospheric summer/winter easterly/westerly jets to the lower thermosphere westerly/easterly jets through GW momentum deposition.

The MLT region is accessible to radar wind measurements, although standard methods only deliver limited temporal and thus spectral resolution of GW. On the other hand, however, radar measurements are cost-effective, reliable, and independent of weather and thus may provide long-term datasets of local background prevailing wind and GW information. Consequently, some effort has been undertaken to analyse GW changes in the MLT also in connection with background wind (e.g., Gavrilov et al., 1999; Jacobi et al., 2006; Hoffmann et al., 2011). GWs are filtered in the mesosphere through the zonal wind jets. Eastward/westward travelling GWs usually encounter critical lines in the winter/summer mesosphere, where the phase speed equals the wind speed. Therefore, essentially westward/eastward travelling GWs remain in the upper mesosphere. According to linear theory, in the case of wave saturation the GW amplitudes equal the intrinsic phase speed, so that in summer stronger mesospheric easterlies are expected be connected with larger GW amplitudes, while in winter stronger mesospheric westerlies may lead to larger GW amplitudes, provided similar distributions of GW horizontal phase velocities.

Jacobi et al. (2006) have found a possible positive correlation of solar activity and GW proxies derived from Collm (reference point 52.1°N, 13.2°E) wind measurements. They attributed this correlation to the possible effect of a solar cycle variation of the mesospheric jet, which is stronger during solar maximum both in winter and in summer. Hoffmann et al. (2011), analysing 22 years of medium frequency radar wind data over Juliusruh, Germany, showed a long-term increase of the mesospheric wind jet and consequently an increase of GW kinetic energy in summer.

The Collm dataset used by Jacobi et al. (2006) had been extended until 2007. Therefore, a 24 year dataset of gravity wave proxies is available and analysed here with respect to long-term linear trends as well as decadal variability, the latter assumed to be driven by the 11-year solar cycle. The dataset thus represents an

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update of the one used by Jacobi et al. (2006). In the following Section 2 the method of GW proxy analysis is briefly described. Section 3 presents results of long-term mean prevailing winds and gravity wave proxies. In Section 4, analysis of trends and solar activity dependence is performed using linear least-squares fitting. In Section 5 the results are discussed. Section 6 concludes the paper.

2. LF wind measurements and gravity wave proxy analysis

From 1959–2007, MLT winds have been measured at Collm, Germany, using the spaced receiver method in the low-frequency (LF) range at oblique incidence. Several commercial transmitters have been used, one of them located at Zehlendorf near Berlin (frequency 177 kHz), at a distance to Collm of about 165 km. The lower ionospheric reflection point of the sky wave registered at Collm is located at 52.1°N, 13.2°E. Horizontal winds have been analysed using the similar fade method at three receivers at 300 m distance. The applied method makes use of the fact that corresponding maxima or minima of similar fadings of the sky wave are registered at the different receivers with a time delay with respect to each other, which is proportional to the drift velocity of electron density fluctuation patterns at the LF reflection height near 90 km. The method has been described in detail, e.g., by Schminder and Kürschner (1994). Since 2004, meteor radar measurements are carried out at Collm with several years of overlapping measurements (e.g., Jacobi et al., 2009; Jacobi, 2011).

The LF reflection height has been measured from late 1982 to 2007 on 177 kHz through comparison of the phase of the ground wave and sky wave on a side-band frequency near 1.8 kHz (Kürschner et al., 1987). Since the group velocity of radio waves in the lower ionosphere is lower than the speed of light, the resulting altitudes represent virtual heights, and these exceed the real heights by several kilometres. A correction, based on the comparison of semidiurnal tidal phase positions at corresponding heights using meteor radar (Jacobi, 2011) has been applied. Monthly median reflection heights range between 80 and 95 km (Fig. 1).

LF reflection heights change in a regular manner in the course of a day, since they broadly represent the altitude of a fixed electron density, which equals the critical frequency at oblique incidence. In addition, above all in summer regular data gaps appear during daylight hours (Fig. 1b). Therefore, estimates of daily height profiles of winds are not available. Monthly prevailing winds have thus been calculated from 1 month of half-hourly mean zonal and meridional winds and reflection heights. A least-squares fitting of the prevailing wind and the semidiurnal tide has been applied to these data. There, a second order height-dependence of the regression coefficient has been assumed. The method has been described, e.g., in Schminder and Kürschner (1988, 1994) and Jacobi (2011). Right-hand circular polarization of the horizontal tidal components has been assumed (Kürschner, 1991).

Proxies of gravity wave variance in the period range 0.7–3 h (for details, see Gavrilov et al., 2001, and Jacobi et al., 2006) have been calculated using the squared differences u'^2 and v'^2 of subsequent half-hourly mean zonal or meridional winds, respectively, provided that the reflection height difference between these two time intervals does not exceed 1 km. Note that this means that, on an average, GW proxies at different altitudes preferably refer to different times of the day (see Fig. 1). The monthly mean variances have been calculated using data of 1 month within overlapping 7 km vertical windows, and the reference height was attributed to the centre of the respective height window. This nominal height may differ from the real height if the wind velocity pairs used for

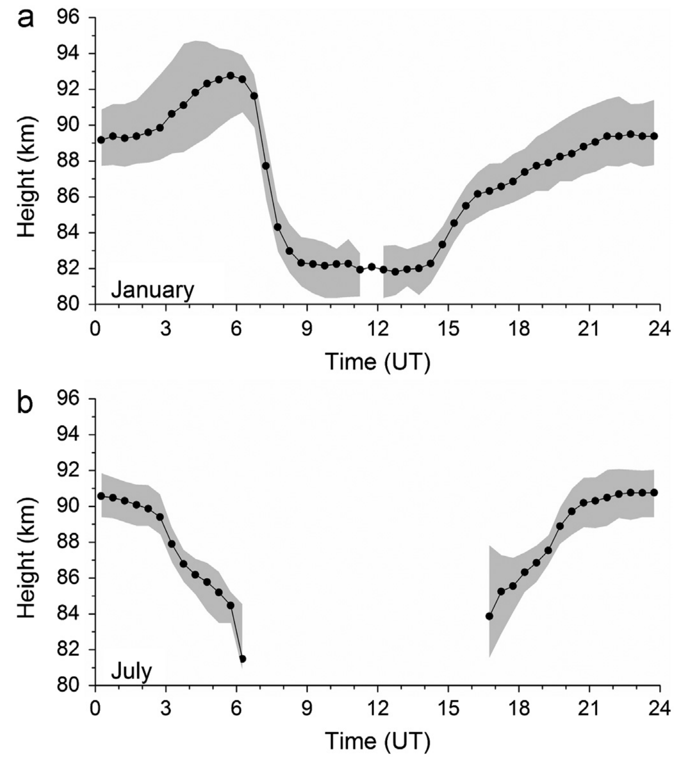

Fig. 1. From 1983 to 2007 median reflection heights in (a) January and (b) July. Upper and lower quartiles are indicated by the shaded area.

calculating the variance are unevenly distributed with height. The procedure is described in Gavrilov et al. (2001) and Jacobi et al. (2006), but they have used 10 km height windows and virtual heights. It should be stressed here that the GW proxy results refer to a specific frequency window only, and no information about the GW wavelength is provided. Therefore, the results presented in the following are of qualitative nature.

To illustrate the long-term variability of the mean wind and GW parameters, as an example in Fig. 2 time series of 3-monthly mean total variances $\sigma^2=u'^2+v'^2$ and zonal mean wind v_{zon} are presented for October–December means at 85 km altitude. The 3-monthly mean F10.7 solar radio flux, given in sfu (1 sfu$=10^{-22}$Wm^{-2} Hz^{-1}) is added. The data are shown from 1984, since until late 1982 the reflection heights have been recorded on an hourly base only so that GW proxies could not be calculated. Linear trends, although not necessarily being significant are added. A positive long-term trend is visible in both parameters, (0.8 ± 0.5 m^{2}s^{-2} yr^{-1} for σ^2 and 0.17 ± 0.10 ms^{-1} yr^{-1} for v_{zon}) as well as an indication for an in-phase decadal variability of GW variance and zonal prevailing wind. This decadal variability is broadly in phase with the 11-year solar cycle. An indication for a similar GW and zonal wind effect has already been shown by Gavrilov et al. (1999) for Shigaraki (35°N, 136°E). Note that in Fig. 2 there is no simple correspondence between GW and zonal wind variability on the interannual time scale. In particular, there is a tendency for an anticorrelation between GW amplitudes and zonal wind during solar maximum. For example, the maximum GW variance is observed in 1990 and 2002, when local minima of zonal wind are found, and also in 1986 the minimum of zonal wind is not accompanied with a variance minimum. On the contrary, in 1985 there is a minimum of GW variance and a local maximum of the zonal wind. At this point one may only speculate about the reasons for such behaviour, which may include varying GW sources, or GW filtering processes at lower levels that cannot be observed by the LF registrations.