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The seasonal cycle of gravity wave momentum flux and forcing in the high latitude northern hemisphere mesopause region

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A new generation all-sky SKiYMET meteor radar, optimized to measure high-frequency gravity wave momentum flux, was installed in Trondheim, Norway (63.4°N, 10.5°E), and has been providing near-continuous measurements since September 2012. Using the system's first full calendar year of observations the seasonal cycle of gravity wave momentum flux and forcing in the mesopause region is studied. The vertical flux of zonal momentum is observed to change from westward to eastward with increasing altitude in winter, and from eastward to westward in summer. This vertical divergence results in westward gravity wave forcing in winter, and eastward forcing in summer. It is shown that the seasonal cycle in gravity wave momentum flux and forcing can be interpreted in terms of selective filtering of a uniform spectrum of vertically propagating GWs between the surface and the mesopause region.

1. Introduction

It is widely acknowledged that gravity waves (GWs) are not solely an interesting atmospheric phenomenon, but play an important role in atmospheric dynamics due to their ability to redistribute energy and couple different atmospheric layers (e.g. Nappo, 2002; Fritts and Alexander, 2003). Indeed, GWs are understood to be the main driver of the general circulation in the quiescent mesosphere/lower thermosphere (MLT) (e.g. Holton, 1983; Fritts and Alexander, 2003 and references therein). GWs propagating upward from the lower atmosphere encounter selective filtering in the stratospheric winds (Lindzen, 1981), which in turn determines the GW spectrum and its corresponding momentum flux reaching the MLT. This process plays an important role in establishing the summer to winter pole circulation in the MLT, thus driving the MLT away from radiative equilibrium (e.g. Holton, 1983; Vincent, 2009).

Due to their relatively small scales, GWs are generally not resolved in global circulation and climate models, but rather their effects are parameterized in order to produce realistic wind and temperature fields (Geller et al., 2013), although it must be noted that high resolution models capable of explicitly resolving an increasing portion of GW scales are now becoming available (e.g. Becker, 2009). A key parameter to guide and constrain these parameterizations is the GW momentum flux, and in particular knowledge of its seasonal and latitudinal variation is important (Espy et al., 2006; Geller et al., 2013). Different methods have been used to study GWs in the MLT. One such method is the use of satellite instruments like Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) to measure GW momentum flux (e.g. Ern et al., 2011), where GW amplitudes are derived from measured temperature profiles. The major advantage of this technique is that it provides global scale coverage and provides information regarding latitudinal variations, albeit for a limited range of GW temporal and spatial scales. However, no directional information about the GW momentum flux can be obtained using this method. Directional GW momentum flux in the MLT region can be derived using various other techniques, including combined radar and airglow observations (e.g. Gardner et al., 1999; Espy et al., 2004, 2006), and studies using dual-beam radars (e.g. Vincent and Reid, 1983; Fritts and Vincent, 1987; Janches et al., 2006; Fritts et al., 2006).

A generalization of the dual-beam method (Vincent and Reid, 1983) was proposed by Hocking (2005), enabling GW momentum flux observations in the MLT using meteor radar measurements, and is based on the notion that fluctuations in the wind field, after removal of a background wind, represent the true wind variability due to GWs (Hocking, 2005). The technique has been used to study momentum fluxes using standard meteor radars (Hocking et al., 2001) at high latitude (Hocking, 2005; Placke et al., 2011a), mid-latitude (Hocking, 2005; Placke et al., 2011a, 2011b), and tropical

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sites (Antonita et al., 2008). Due to the relatively large network of meteor radars (Hocking, 2005) as well as their capability to obtain continuous measurements, meteor radars appear to be well suited to study latitudinal variation as well as the seasonal cycle of the GW momentum flux.

A limiting factor in the determination of GW momentum fluxes using meteor radars is the meteor count rate and zenith angle distribution (Hocking, 2005, 2011; Andrioli et al., 2013). When meteor counts are low, the use of long averaging time intervals on the order of one month is necessary, compromising the temporal resolution with which the GW momentum flux variability can be derived. In order to optimize meteor radars to determine GW momentum fluxes, a new generation SKiYMET system was developed and first deployed on Tierra del Fuego (53.8°S, 67.8°W) (Fritts et al., 2010a,b). Here, 8 transmitter antennas are combined in order to achieve high peak powers and to direct most of this power in the area between 15° and 50° zenith angle, resulting in high meteor count rates in the region of interest for the determination of GW momentum fluxes (Fritts et al., 2010a,b). Indeed, using the meteor distribution detected with the optimized system, Fritts et al. (2010a) showed that GW momentum flux estimates remain reliable when averaging time scales were reduced to as low as 10 days.

The first northern hemisphere SKiYMET meteor radar optimized to measure GW momentum fluxes is located in Trondheim, Norway (63.4°N, 10.5°E), and has been operational since September 2012. This study presents the first observations of the seasonal cycle of GW momentum flux and forcing during 2013 obtained with this new generation radar. The system design and data analysis techniques are described in Section 2. As meteor statistics are an important factor when determining GW momentum fluxes, meteor statistics over 2013 are presented in Section 3. Afterwards, the seasonal cycle in the horizontal winds and the high-frequency GW momentum flux and forcing are presented. In Section 4, the GW momentum flux and forcing are discussed in light of previous observations as well as the background wind field.

2. System specifications and data analysis

2.1. System specifications

The Trondheim Meteor Radar is an all-sky SKiYMET meteor radar (Hocking et al., 2001) located in Trondheim, Norway (63.4°N, 10.5°E) and has been operating near-continuously since September 2012. The system is similar in design to the SAAMER and DrAAMER radars (Fritts et al., 2010a,b, 2012), and is optimized to measure GW momentum fluxes in addition to traditional meteor radar parameters such as horizontal winds and temperatures. To this end, the transmitter array consists of 8 three-element Yagi antennas in a circular orientation, supplying a peak power of 30 kW. During normal operation most of the power is directed into eight beams at 45° azimuth increments, with peak powers around 35° off-zenith and a majority of meteors detected between 15° and 50° zenith angle (see e.g. Fritts et al., 2010b, their Fig. 1). Other transmitter phasings are also possible, allowing for different beam-modes. One of the set-ups available is a vertical beam-mode, in which the radar ran for 2 consecutive days in July 2013 (9.58 UT 10/7–11.42 UT 12/7) without any detrimental effect on routine observations.

The return signal is detected on 5 three-element Yagi antennas, spaced at 2λ and 2.5λ, increasing detection precision. Details on receiver antenna layout, and routine meteor positioning and radial velocity determination can be found in Hocking et al. (2001).

The radar frequency of 34.21 MHz is optimized for meteor detection at peak meteor ablation altitudes. Peak count rates are observed around 90 km, and generally enough meteors are detected in the range of 70–100 km for the derivation of horizontal winds throughout this region (see also Section 3.1). A pulse repetition frequency of 925 Hz and a pulse width of 2 km were used throughout 2013.

Data coverage for 2013 was 96%, with brief periods of downtime due to maintenance and system failure. Data gaps of more than 24 h are present from 05/03 (12 UT) to 05/04 (18 UT), 07/24 (0 UT) to 07/26 (14 UT), 08/04 (13 UT) to 08/05 (12 UT), 08/10 (18 UT) to 08/13 (12 UT), and 08/23 (20 UT) to 08/27 (12 UT). Between 05/26 and 06/07 a power amplifier problem caused a slightly distorted beam pattern and a 25% reduction in transmitter power.

2.2. Data analysis

Horizontal winds between 70 and 100 km are determined for 60-min time intervals and several altitude intervals by performing a least-squares best fit to the measured radial velocities when at least 7 meteors are present in the altitude interval (Hocking et al., 2001). The altitude intervals used are 8 km (70–78 km), 4 km (78–82 km), 2 km (82–96 km), and again 4 km (96–100 km) to correct for the change of meteor count rates with altitude. In the horizontal wind determination, as well as all other analysis described in this study, only unambiguously detected meteors between 15° and 50° zenith angle have been used. In addition to the horizontal wind, the mean meteor time and height (defined as the average meteor detection time and altitude) are determined for each individual time–height interval. These parameters reflect the non-uniform distribution of meteors in time and altitude, and using these parameters ensures that the derived horizontal winds are assigned to the altitude and point in time best representing their occurrence.

From the hourly zonal and meridional winds in each altitude interval, moving averages were created by performing a least-squares fit over a time period of 4 days (time-stepped by 1 day) using an offset representing the 4-day moving-average horizontal wind, together with oscillations with periods of 48- (representing a 2-day planetary wave), 24-, 12-, and 8-h (tides) when at least half of the data were present in the time interval.

High-frequency GW momentum fluxes were derived for four 4 km altitude intervals between 80 and 96 km in a manner similar to that described in de Wit et al. (2014). A proper removal of the background wind is crucial in order to obtain reliable momentum flux estimates (Andrioli et al., 2013), especially in regions where large amplitude high frequency tides are present, as is the case in the Scandinavian MLT (e.g. Mitchell et al., 2002). The hourly mean horizontal winds were linearly interpolated in height and time to the altitude and time of each individual meteor detection. The component of this meteor-specific background wind along the meteor's line-of-sight was subtracted off the individual meteor's observed radial velocity to derive the residual velocity perturbation due to high-frequency GWs. Then, using the matrix-inversion method proposed by Hocking (2005) 90-min momentum fluxes (45 min periods centered around the nominal time, shifted in 1-h time steps) are calculated from the velocity perturbations when at least 30 meteors are available. These hourly values are then combined in monthly (cf Fig. 4) or 10-day moving averages (cf Fig. 5). When calculating these averages and corresponding $1-\sigma$ standard errors of the mean, momentum fluxes obtained from the inversion of a near-singular matrix or with an absolute value exceeding 300 $m^2\,s^{-2}$ are discarded as, although mathematically correct, these results are considered to be non-physical (Hocking, personal communication). Using this method, momentum fluxes from high-frequency GWs with periods up to the order of 2–3 h can be derived (Hocking, 2005). Although the GW spectrum

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