Journal of Atmospheric and Solar–Terrestrial Physics xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar–Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Observational indications of downward-propagating gravity waves in middle atmosphere lidar data

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ARTICLE INFO

Keywords:
Gravity waves
Middle atmosphere
Lidar
Downward-propagating waves

ABSTRACT

Two Rayleigh lidars were employed at a southern-hemisphere mid-latitude site in New Zealand (45°S) and a northern-hemisphere high-latitude site in Finland (67°N) in order to observe gravity waves between 30 and 85 km altitude under wintertime conditions. Two-dimensional wavelet analysis is used to analyze temperature perturbations caused by gravity waves and to determine their vertical wavelengths and phase progression. In both datasets, upward phase progression waves occur frequently between 30 and 85 km altitude. Six cases of large-amplitude wave packets are selected which exhibit upward phase progression in the stratosphere and/or mesosphere. We argue that these wave packets propagate downward and we discuss possible wave generation mechanisms. Spectral analysis reveals that superpositions of two or three wave packets are common. Furthermore, their characteristics often match those of upward-propagating waves which are observed at the same time or earlier. In the dataset means, the contribution of upward phase progression waves to the potential energy density E_p is largest in the lower stratosphere above Finland. There, E_p of upward and downward phase progression waves is comparable. At 85 km one third of the potential energy carried by propagating waves is attributed to upward phase progression waves. In some cases E_p of upward phase progression waves far exceeds E_p of downward phase progression waves. The downward-propagating waves might be generated in situ in the middle atmosphere or arise from reflection of upward-propagating waves.

1. Introduction

Atmospheric gravity waves represent an important coupling mechanism between the lower and the middle atmosphere with strong effects on the energy budget and general circulation of the atmosphere (Holton, 1982). Major sources of gravity waves are flow over topography, convection, spontaneous adjustment and dynamical processes related to the tropospheric jet stream (see Fritts and Alexander, 2003; Plougonven and Zhang, 2014, for reviews of gravity waves).

From tropospheric sources, gravity waves propagate horizontally and vertically according to their group velocity which determines the direction of energy propagation. The vertical group velocity is thereby of opposite sign compared to the vertical phase velocity, i.e. downward phase progression means upward energy/wave propagation (Nappo, 2013). The amplitudes of the waves grow with altitude due to the decreasing density. Critical-level filtering by the background wind may modify vertical propagation. Breaking of large-amplitude gravity waves in the mesopause region may generate small-scale gravity waves visible, for example, in polar mesospheric clouds (Chandran et al., 2009) and imagery of the airglow layer (Nielsen et al., 2006). Interaction with the mean flow may also cause damping, refraction, reflection and ducting of waves (Fritts and Alexander, 2003). Reflection of primary waves, such as from regions with large vertical gradients of the horizontal wind, results in waves that propagate downward. Idealized model simulations predict the generation of secondary waves by breaking of primary waves in the stratosphere and mesosphere (Satomura and Sato, 1999; Zhou et al., 2002). Downward-propagating gravity waves may also be generated in situ in the middle atmosphere, e.g. in the polar night jet region (Sato and Yoshiki, 2008). These waves, either generated in situ or by reflection of primary waves, may contribute to the downward coupling from the mesosphere to the lower stratosphere.

Downward-propagating waves, i.e. waves with downward energy propagation, were observed in the lower stratosphere by radiosondes at

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http://dx.doi.org/10.1016/j.jastp.2017.03.003
Received 9 July 2016; Received in revised form 9 February 2017; Accepted 7 March 2017
1364-6826/

Please cite this article as: Kaifler, N., Journal of Atmospheric and Solar–Terrestrial Physics (2017), http://dx.doi.org/10.1016/j.jastp.2017.03.003

sites inside the polar vortex or close to its edge (Sato and Yoshiki, 2008; Moffat-Griffin et al., 2011; Murphy et al., 2014). Moffat-Griffin et al. (2011) report that up to 60% of all waves propagate downward and carry about the same amount of energy compared to upward-propagating waves, which is in accordance with the observations by Murphy et al. (2014). There are only few observations in the upper stratosphere and above as radiosondes seldom reach altitudes above 30 km. Wilson et al. (1991) and Yamashita et al. (2009) derived the gravity wave potential energy density of waves with positive ground-based vertical phase velocity and thus potentially downward energy propagation at mid- and high-latitude sites from lidar measurements by applying two-dimensional Fourier analysis. Wilson et al. (1991) attributed on average one third of the gravity wave energy density to downward-propagating waves in the 30–45 km altitude range at a mid-latitude site, whereas (Yamashita et al., 2009) report values up to 50% in the same altitude range at two Antarctic sites. Model simulations by Sato et al. (2012) also show significant downward energy propagation south of the southern Andes in the lower stratosphere in winter. To the knowledge of the authors, no previous observational studies on downward-propagating gravity waves in the upper mesosphere exist.

We use observational data acquired during two field campaigns dedicated to the study of atmospheric gravity waves. The DEEPWAVE campaign was based at New Zealand during austral winter 2014. Its goal was to quantify gravity wave dynamics and effects from the source regions to the regions of dissipation (Fritts et al., 2016). The GW-LCYCLE2 campaign took place in winter 2015/2016 in northern Scandinavia as part of the Role of the Middle Atmosphere in Climate (ROMIC) programme, with the goal to study dynamical processes in the polar winter atmosphere. Both locations are close to the polar vortex edge where stratospheric wave activity is largest (Whiteway et al., 1997; Baumgaertner and McDonald, 2007). New Zealand is a “gravity wave hotspot” (Hoffmann et al., 2016), and the Scandinavian Mountains are also known for the occurrence of large-amplitude mountain waves (Dörnbrack et al., 1999). From the global maps of stratospheric gravity wave variances by Wu and Eckermann (2008), comparable wave activity during winter is inferred for New Zealand and northern Scandinavia. Both campaigns utilized comprehensive sets of airborne and ground-based instrumentation including a ground-based lidar. The lidar instruments produced large datasets of high-resolution temperature measurements covering the middle atmosphere from 30 up to 85 km altitude.

In this paper, we apply an advanced spectral analysis method using two-dimensional wavelets in order to classify waves based on their vertical phase progression. Downward-propagating wave packets are identified by upward phase progression $c_z = \omega/m$, where ω is the ground-based, observed frequency and m the vertical wavenumber. Regarding this approach, (Fritts and Alexander, 2003, par. 56) note that for waves with a horizontal phase velocity comparable to and opposed to the mean wind, a false assignment of the direction of energy propagation occurs due to Doppler shifting. Unfortunately, no co-located wind measurements are available at the lidar sites. We utilize meteor radar data and ECMWF model data in our interpretation and give additional arguments that the observed waves are downward-propagating. From both lidar datasets, we estimate the gravity wave background and present selected events in order to characterize downward-propagating gravity waves in the middle atmosphere. These are the first observations of downward-propagating gravity waves at mesospheric altitudes and we therefore aim to give a thorough description of the observations. Although conclusive evidence and identification of generation processes relies on additional wind information and modelling and is beyond the scope of this paper, we speculate on possible sources and generation mechanisms based on the data at hand in order to stimulate further research.

Instrument details and key figures of the datasets are given in Section 2. The analysis involving two-dimensional wavelet transformations is described in Section 3. In Section 4 the analysis methods are applied to observational data in order to characterize the gravity wave background. Six cases are selected for further investigation. These are described in detail in Section 5. In Section 6 the interpretation concerning the sources and propagation of the observed wave packets are discussed with respect to the influence of the background wind. A summary is given in Section 7.

2. Data

Middle atmospheric temperature measurements obtained by two ground-based Rayleigh lidars are used in this study. The Temperature Lidar for Middle Atmosphere Research (TELMA) and the Compact Rayleigh Autonomous Lidar (CORAL), both recently developed by the German Aerospace Center (DLR), are transportable, semi-autonomous middle atmosphere lidars. Both systems are equipped with pulsed Nd:YAG lasers with 12 W average power at 532 nm wavelength and telescopes of 63 cm diameter for reception of the atmospheric return signal. Two height-cascaded receiver channels are used to increase the dynamic range. From the measured photon count profiles, atmospheric density is inferred and temperature profiles $T(z)$ are obtained by top-down integration assuming hydrostatic equilibrium (Hauchecorne and Chanin, 1980). At the top altitude around 100–110 km, the integration is seeded by SABER temperature measurements. Typical uncertainties in temperature measurements are less than 5 K at 80 km and less than 1–2 K at 60 km and below for 20 min resolution. In this paper, we analyze lidar temperature observations in the 30–85 km altitude range.

The TELMA instrument was deployed to Lauder, New Zealand (45.0°S, 169.7°E), during the DEEPWAVE campaign in austral winter 2014 (Fritts et al., 2016; Kaifler et al., 2015). The second dataset was obtained by the CORAL lidar during the GW-LCYCLE2 campaign at Sodankylä, Finland (67.4°N, 26.6°E), in winter 2015/2016. In total, 1021 h of atmospheric temperature data are available for analysis. Here, we focus on continuous observations of more than 8 h duration. This leaves 38 nights (402 h) from the DEEPWAVE dataset in the period 30 June 2014 – 27 October 2014, and 26 nights (292 h) from GW-LCYCLE2 between 7 October 2015 and 21 March 2016. The two subsets amount to 694 h in total. The data are organized in time-height matrices with $\Delta t = 5\ \text{min} \times \Delta z = 540\ \text{m}$ resolution. Due to smoothing of raw photon count data in the temperature retrieval, the effective resolution of independent temperature observations is 20 min×2100 m.

3. Method

Gravity waves manifest themselves by temperature perturbations $T'(z, t)$ superposed on the background temperature profile $T_0(z)$. Following Ehard et al. (2015), we extract $T'(z, t)$ from the observed temperature $T(z, t)$ by applying a 5th order Butterworth filter with a cutoff wavelength of 15 km. The nightly mean of the background temperature field

$$T_0(z) = \overline{T(z, t) - T'(z, t)} \tag{1}$$

is used to calculate the squared Brunt-Vaisälä frequency $N^2(z)$ which represents the ambient atmospheric static stability. Using T_0, T', N^2 and the acceleration due to Earth's gravity, g, the gravity wave potential energy density normalized by mass

$$E_p(z) = \frac{1}{2}\frac{g^2}{N^2}\overline{\left(\frac{T'}{T_0}\right)^2} \tag{2}$$

is derived.

Assuming the temperature perturbations T' are caused by a superposition of quasi-monochromatic waves, we decompose the observed gravity wave field using wavelet transformations with two-dimensional Morlet wavelets (Wang and Lu, 2010; Kaifler et al., 2015). The properties of the Morlet wavelet are determined by two parameters: