Journal of Atmospheric and Solar-Terrestrial Physics 140 (2016) 23–33

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Research paper

Investigation of gravity wave activity based on operational radiosonde data from 13 years (1997-2009): Climatology and possible induced variability

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ARTICLE INFO

Article history:
Received 14 September 2015
Received in revised form
21 January 2016
Accepted 22 January 2016
Available online 23 January 2016

Keywords:
Gravity waves
Climatology
Radiosondes
Extratropical cyclone

ABSTRACT

Atmospheric gravity waves (GWs) are important for the dynamics of the atmosphere. The analysis of 13 years of routine radiosonde data from Prague (50.01°N, 14.27°E) with temporal highly resolved temperature, pressure and wind measurements is presented in order to derive a climatology of gravity wave activity in the lower stratosphere. An annual cycle with a maximum during winter and a minimum during summer is identified. Gravity wave activity is twice as high during winter as during summer. Winter periods are investigated by wavelet analysis. They show similar periods in vertical flux of horizontal momentum and pressure variance time series. These features may be attributed to planetary waves. When analyzing individual years, maxima of gravity wave activity and vertical flux of horizontal momentum often appears together with minima in surface pressure. We speculate therefore that at least parts of the interannual variations of gravity wave activity may due to cyclones.

1. Introduction

It is widely accepted that gravity waves (GWs) play a significant role in the dynamics of the atmosphere as they can transport horizontal momentum and energy even over large distances. These aspects are well addressed by a multitude of publications within the past decades (see, for example, Hines, 1960; Lindzen and Holton, 1968; Fritts and Alexander 2003). Very often, GWs are to be handled as so-called subgrid-scale processes and are therefore mainly represented via parameterizations in both numerical climate and weather-forecast models (e.g. Manzini and McFarlane, 1998; Choi and Chun, 2011; Orr et al. 2010; Stevens et al., 2013). These models frequently turned out to being considerably sensitive to such parameterizations (e.g. Alexander et al., 2010). Therefore, there is an ongoing need to improve them.

Among topographic generation, shear generation and geostrophic adjustment as well as convective systems are known as prominent tropospheric sources of GWs (Holton, 1983; Fritts and Alexander, 2003). Primarily, orographically excited GWs are usually implemented into models (e.g. McFarlane, 1987; Kim and Arakawa, 1995). McFarlane (1987) presented the results of introducing a simple wave drag parameterization into the Canadian Climate Center general circulation model. A new approach to overcome the deficiency of the model to properly treat the enhancement of drag due to low-level wave breaking by including additional statistical information on subgrid-scale orography in the input of the parameterization was presented by Kim and Arakawa (1995). Further investigations were made by Pulido et al. (2012). They developed an inverse technique using data assimilation principles to estimate gravity wave parameters. By defining a cost function that measures the difference between unresolved drag inferred from observations and the gravity wave drag (GWD) calculated with a parameterization scheme, they provided a robust parameter estimation over a broad range of prescribed parameters. This parameterization agrees better with the observed GWD at high latitudes, if the parameters are allowed to vary with latitude. However, the agreement is either good at the upper or at the lower part of the profile (up to 10 hPa). Orr et al. (2010) investigated how a non-orographic GWD parameterization improves middle atmosphere climate and forecasts of the ECMWF (European Centre for Medium-Range Weather Forecasts) model. The implementation into the model replacing Rayleigh friction leads to a more realistic parameterized gravity wave drag and horizontal distribution of momentum flux in the stratosphere. Choi and Chun (2011) studied the convective source and momentum flux spectra of a parameterization of convective gravity wave drag (GWDC) in a three-dimensional spectral space using mesoscale numerical

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http://dx.doi.org/10.1016/j.jastp.2016.01.014
1364-6826/

simulations for various ideal and real convective storms. The authors determined two parameters, namely the moving speed of the convective source and the wave propagation direction. These parameters were included in the GWDC parameterization by Song and Chun (2005).

GWs are observed by means of several techniques, implying that each measuring technique has its special limitations on GW parameters like wavelength. As global gravity wave characteristics depending on time, height and geographical location are needed for model input parameters, satellite-based measurements are very useful. Besides satellites (e.g., Preusse et al., 2002; Ern et al., 2004) other measurement techniques include rocketsondes (e.g., Hirota and Niki, 1985; Hamilton, 1991; Eckermann et al., 1994; Wüst and Bittner, 2006), lidar and radar observations (e.g., Sato, 1994; Mitchell et al., 1994; Sato et al., 1997; Riggin et al., 1997; Li et al., 2010), aircraft (e.g., Nastrom et al., 1987; Dörnbrack et al., 2002; Doyle et al., 2002) and radiosondes (e.g., see Vincent et al., 1997; Yoshiki and Sato, 2000; Wang and Geller, 2003; Gong et al., 2008, Zhang et al. 2014, Kramer et al., 2015). Moreover, it is possible to derive gravity wave characteristics in the upper mesosphere from airglow observations (Hines and Tarasick, 1987; Swenson et al., 2000; Bittner et al., 2002; Schmidt et al., 2013). Radiosonde data has proven to be suitable for the study of gravity waves in the troposphere and lower stratosphere. Meteorological institutions and national weather services are releasing radiosondes in a regular manner (for synoptic purposes) providing also information on gravity wave activity in the lower atmosphere from a multitude of sites worldwide. Hamilton and Vincent (1995) demonstrated the advantage of the vertically high resolved measurements of meteorological parameters such like temperature, pressure, humidity and wind. Detailed gravity wave studies based on such data provide valuable statistical information on the seasonal and spatial variability of gravity waves and their sources, propagation and dissipation (see also e.g. Allen and Vincent 1995; Wang and Geller 2003; Moffat-Griffin et al., 2011).

As mentioned above, convection due to cyclones is a prominent gravity wave source. Studies on their effectivity in terms of GW excitation including the estimation of GW parameters (wavelengths, phase speeds, propagation directions) in all atmospheric height-layers are needed. This holds especially in the context of predicting changes of storm/cyclone intensity (Graham and Diaz, 2001; Ulbrich et al., 2007; Kramer et al., 2015) possibly going along with changing cyclone induced GW activity. Additionally, studies about improvements in operational tropical cyclone track forecasts (e.g. Aberson, 2003; Jung et al., 2011) and operational numerical weather forecast (e.g. Boybeyi et al., 2002; Irvine et al., 2011) request such studies.

The focus of this work is on characterizing GW activity due to cyclone activity at Prague on the basis of 13 years of routine radiosonde measurements. The paper is organized as follows. In Section 2 the radiosonde data set used is described in detail, whereas Section 3 gives a short introduction on techniques applied for data processing and estimation of gravity wave parameters. Section 4 is devoted to the discussion of the results. In Section 5 main results are summarized and concluding remarks are given.

2. Data

The Czech Hydrometeorological Institut (CHMI) performs four operational radiosonde launches each day at 0, 6, 12 and 18 UTC at Prague (50.01°N, 14.45°E). Analysis of this work is based on a 13-year time series (1997-2009) of these routine radiosonde measurements, which include 17523 releases. Most radiosonde releases are performed using Vaisala RS92-KL radiosondes, but

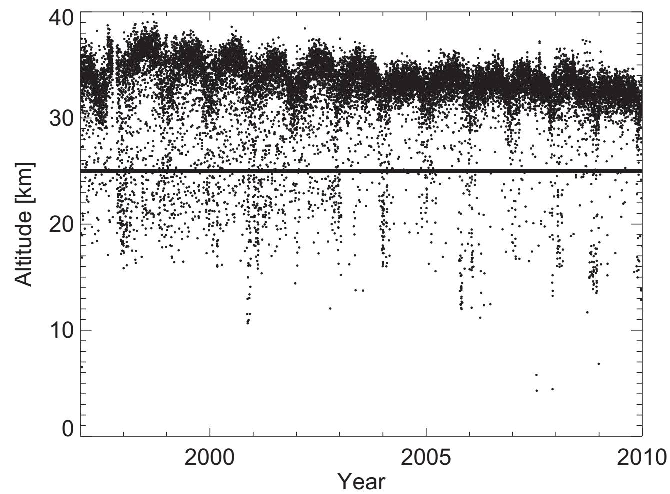

Fig. 1. Times series of maximum altitudes from radiosonde measurements at Prague during 1997-2009. Solid line denotes the 25 km minimum altitude limit used for analyses.

different types of balloons (Cosmoprene KKS800, TOTEX TA1000, TOTEX TX800, and TOTEX TA800).

Temperature, pressure and humidity data are available with an accuracy of about 0.5 K, 0.6-1 hPa and 5% relative humidity. An accuracy of less than 0.2 m/s for the wind speed is given for the Vaisala RS92-SGP radiosonde. It is 0.7 m/s for Vaisala RS92-KL. Data are sampled every 5 s during a balloon ascent and the vertical velocity of the balloon accounts for about 5 m/s; this results in a vertical resolution of about 25 m. The radiosondes typically reach altitudes of 25-35 km (see Fig. 1). Radiosondes which do not reach at least 25 km height are discarded from further analysis (1402 radiosonde launches are therefore excluded). Investigations of how many profiles of the whole period depending on month have to be discarded, show that January, November and December have the biggest numbers. In 1997 the biggest percentage of yearly released radiosondes did not reach the 25 km level. Also the following years (1998-2002) exhibit much more exclusions than the rest (2003-2009). Note that the maximum altitude the radiosondes reached reveals an annual cycle (see Fig. 1). The highest altitudes are reached during the summer period, while balloons burst at lower altitudes during winter. Beside this annual variation of the maximum ascent heights, the peak heights decrease until about 2004. This effect might be at least partially due to several changes in balloon size and type (personal communication with P. Skrivankova, CHMI) during that period. Another aspect could be stratospheric cooling due to climate change (see e.g. Thompson et al., 2012). Balloons burst earlier at low temperatures. This feature is not relevant for our study and will therefore not be regarded here. Since 2004 the annual cycle of maximum heights is almost the same for every year.

3. Methods

GW induced fluctuations are separated from every individual radiosonde profile. A linear superposition principle of GW perturbations for temperature, zonal and meridional wind (T', $u'$and v') on a background structure ($\bar{T}$,$\bar{u}$ and $\bar{v}$) is assumed: $T = \bar{T}+T'$(e.g., Pfenninger et al., 1999; Zhang et al., 2012). A sophisticated cubic spline method is used (Bittner et al., 1994). Vertical resolution of filtered data is 100 m; the cut-off wavelength of the low-pass filter is chosen to be 7 km. This limit is used in order to focus only on mesoscale perturbations and to exclude large-scale circulation patterns such as planetary waves. A typical