Journal of Atmospheric and Solar-Terrestrial Physics 135 (2015) 126–135

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Research paper

Analysis of synoptic scale controlling factors in the distribution of gravity wave potential energy

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ARTICLE INFO

Article history:
Received 14 March 2015
Received in revised form
22 October 2015
Accepted 23 October 2015
Available online 24 October 2015

Keywords:
Synoptic scale
Gravity waves
Extratropical cyclones
Subtropical highs
Intertropical Convergence Zone

ABSTRACT

In the past years, global morphology and climatology of gravity waves have been widely studied and the effects of topography and convection systems have been evaluated, but the complete gravity wave distribution could not be explained by these effects. To find the missing controlling factors, a series of synoptic scale analyses is performed in the present study to investigate relationships between synoptic scale factors and potential energy (E_p) associated with gravity waves. Global distribution of E_p during a 12-year period from 2002 to 2013 is derived using temperature profiles retrieved from observations of Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite. Synoptic scale factors obtained from ECMWF Interim reanalysis data are employed to investigate the correlation between synoptic systems and E_p. It is found that E_p values are high around extratropical cyclones over mid-latitudes (30–60°) and around the Intertropical Convergence Zone (ITCZ) over low-latitudes (10–30°). E_p values are low around subtropical highs over both mid- and low-latitudes. This is the first time that a synoptic scale analysis of E_p distribution is performed, and the influence of synoptic scale factors on E_p confirmed.

1. Introduction

Stratospheric wind and temperature are greatly affected by atmospheric waves, such as gravity waves (GWs) and appear as perturbations in these parameters. Waves may be excited by topography (Nastrom and Fritts, 1992), fronts, convective systems, and jet streams (Alexander and Pfister, 1995; Fritts and Nastrom, 1992) over a wide range of vertical wavelengths varying from hundreds of meters to several kilometers in the lower stratosphere and periods ranging from the Brunt–Väisälä period to the inertial period (Fritts and Alexander, 2003).

Wind fields observed by ground-based radars in the lower stratosphere and temperature profiles obtained from lidars in the upper stratosphere have been used to study stratospheric GW activity at high-temporal resolution and also to derive the climatology. Murayama et al. (1994) used the middle and upper atmosphere (MU) radar in Japan to study GW energies from 1985 to 1989 and an annual variation associated with the jet stream was identified. A series of comparative observations were done, and characteristics and variations of GW with height, season, and latitude were summarized by Tsuda et al. (1994), in which, data were obtained from a combination of the above MU radar, two medium frequency (MF) radars, and a lidar. Dhaka et al. (2001, 2002) used the Mesosphere–Stratosphere–Troposphere (MST) radar at Gadanki, India to study GW activity and atmospheric dynamical behavior associated with convection system and found that they are highly correlated with convections after the onset of summer south-west monsoon over Indian peninsula. Using two-day continuous data observed by radars and radiosonde under the Coupling Processes in the Equatorial Atmosphere (CPEA) project, which is a well-coordinated project of radar observation over Indonesia, convection-induced GW were investigated (e.g., Dhaka et al., 2005, 2006). Longitudinal and latitudinal variation of stratospheric GWs were also investigated using in situ measurements, with instruments such as radiosondes and meteorological rockets (e.g., Dhaka et al., 1995; Hamilton, 1991; Hirota, 1984). Compared to radars and lidars, radiosondes provide a larger spatial coverage and are useful to study geographical variations of the stratospheric GW. Allen and Vincent (1995) studied seasonal and latitudinal variations of GWs by using temperature profiles with high-vertical resolution obtained from radiosondes at 18 meteorological stations covering a latitudinal range of 12–68°S and a longitudinal range of 78–159°E. A larger wave energy density was found during the wet season over low-latitudes and during winter over

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http://dx.doi.org/10.1016/j.jastp.2015.10.020
1364-6826/

mid-latitudes, and typically near the tropopause in altitude.

New and reliable observing methods accompanied the development of remote sensing satellites providing global temperature information from lower to upper atmosphere. Tsuda et al. (2000) used temperature profiles obtained from Global Positioning System/ Meteorology (GPS/MET) experiment to study global stratospheric GW activity from April 1995 to February 1997. The global distribution shows that larger potential energy (E_p) values are concentrated near the equator at 20–30 km altitude but over mid-latitudes high E_p is observed at 30–40 km altitude. Also, over mid-latitudes, E_p values are larger in winter months in both hemisphere. An analysis of longitudinal variation of E_p at 20–30 km altitude in latitudinal range of 30–60°N was also performed that showed that E_p values are larger over continents than over the Pacific Ocean.

Following the success of using GPS RO (radio occultation) data to estimate potential energy, data retrieved from other GPS RO satellites were also used to study the global distribution of potential energy. Ratnam et al. (2004a) used Challenging Minisatellite Payload (CHAMP) satellite data to study the global and seasonal variation of stratospheric GW activity, and significant correlations were found between GW activity and tropical deep convections. High E_p values were also noticed during major sudden stratospheric warming (SSW) events over Antarctica in 2002 (Ratnam et al., 2004b). Tsuda et al. (2009) also used CHAMP data to study temporal and spatial distributions of atmospheric wave energy at 19–26 km altitude in the equatorial region. E_p values were compared with convective parameters from outgoing longwave radiation (OLR) data and Tropical Rainfall Measuring Mission (TRMM) satellite and it was found that temporal and spatial distributions of E_p are closely related to convective activity.

Furthermore, temperature data from CHAMP were used to study annual and interannual variations in GW activity in the lower and middle stratosphere (de la Torre et al., 2006; Hei et al., 2008). Over equatorial latitudes, wave activity is highly related to the quasi-biennial oscillation (QBO) of zonal wind, and maximum E_p is observed below the zero zonal wind line corresponding to westerly shears. Using temperature profiles derived from FORMOSAT-3/COSMIC (Constellation Observing System for Meteorology, Ionosphere, and Climate) satellite observations to study equatorial GW potential energy, Alexander et al. (2008) found enhanced E_p occurring around the descending zero wind related to QBO eastward shear. Zhang et al. (2012) used temperature data retrieved from observations of Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite to investigate GW related E_p. An annual variation over middle and high latitudes with winter maxima and a semi-annual variation over tropics with larger E_p values occurring in November–January and May–July were found. The activity of stratospheric GW were stronger in years with westward stratospheric QBO phases than eastward phase implying that the zonal wind acts as a filter for the propagation of stratospheric GW.

The relationship between high activity of stratospheric GW and mesoscale meteorological systems, such as convective systems and jet streams, has been discussed in detail in many previous studies (e.g., Fritts and Nastrom, 1992; Preusse et al., 2001; Vincent and Alexander, 2000; Zhang et al., 2012). In contrast, low activity regions were neglected in these studies. Further, these mesoscale factors could only explain the localized GW distributions near these meteorological systems. A global analysis based on synoptic scale systems over seasonal timescales has not been done and forms the motivation for the current study to completely understand the observed GW distribution.

In the present study, we extracted stratospheric temperature perturbations from TIMED/SABER data between January 2002 and December 2013, and derived E_p associated with stratospheric GW activity over low- and mid-latitudes between 21 and 26 km altitudes. We then analyzed the behavior of wave activity in both high and low-E_p regions and compared them with synoptic scale factors to investigate the correlation between synoptic systems and E_p.

2. Method and data sets

2.1. Theory and method

Stratospheric GWs perturb both wind and temperature and energy density of wave activity is a combination of kinetic energy density and potential energy density that represent these perturbations, respectively. These energy densities are defined as follows.

$$E_0 = E_k + E_p = \frac{1}{2}\left[\overline{u'^2} + \overline{v'^2} + \overline{w'^2} + \left(\frac{g}{N}\right)^2 \overline{\left(\frac{T'}{\bar{T}}\right)^2}\right] \tag{1}$$

$$E_k = \frac{1}{2}\left[\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right] \tag{2}$$

$$E_p = \frac{1}{2}\left(\frac{g}{N}\right)^2 \overline{\left(\frac{T'}{\bar{T}}\right)^2} \tag{3}$$

where E_0, E_k, and E_p are total energy, kinetic energy, and potential energy per unit mass, respectively (Tsuda et al., 2000 and VanZandt, 1985). u', v', and w' are the perturbation terms in the three orthogonal (zonal, meridional, and vertical) components of wind field, and T' is the perturbation from background temperature $\bar{T}$. N is Brunt–Väisälä frequency, which is a function of altitude and potential temperature.

To evaluate total energy density of GWs, the three wind field perturbation terms for E_k and the temperature perturbation for E_p are required. However, wind field is difficult to measure accurately and globally due to limitations associated with wind observations. Measurement of temperature is comparatively easier using remote sensing techniques. With the growing satellite era, huge amount of observational temperature data is available at high temporal and spatial resolutions.

A linear theory of GWs was suggested by VanZandt (1985) to simplify the evaluation of GW activity. According to this theory, the ratio of kinetic to potential energy density, i.e., E_k / E_p is equal to a spectral index p, which is observed to be in the range $3/2 \lessapprox p \lessapprox 2$ with a mean value of about 5/3. Therefore, GW activity can be evaluated by using the E_p term only, which can be derived easily using temperature measurements. The reliability of this linear theory has been confirmed by observational results. Tsuda et al. (2000) presented an annual variation of E_p with an enhancement in winter around Japan region, and this result is consistent with the climatological behavior of E_k as revealed by wind field data observed by the MU radar at Shigaraki, Japan (34.9°N 136.0°E) during 1985 and 1989 (Murayama et al., 1994). Based on these earlier results we assume the ratio of E_k to E_p to be constant in the present study; however, it may not be a valid assumption for some extreme weather systems such as strong jet streams and severe frontal storms.

In the present study, we used a method similar to the one used by Tsuda et al. (2000) to evaluate E_p values and is briefly described below. The vertical wavelength of stratospheric GWs is about 2–10 km (Tsuda et al., 1994), and therefore we applied a band-stop filter with stop band of 2–10 km to each vertical temperature profile, to obtain the background temperature $\bar{T}$. The perturbation term T' is extracted as the difference between T and $\bar{T}$. T is also used to calculate Brunt–Väisälä frequency N. We also used a 2-km sliding window in the calculation of the variance squared term as