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ScienceDirect

Advances in Space Research xxx (2015) xxx–xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Evidence of high frequency gravity wave forcing on the meridional residual circulation at the mesopause region

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Received 24 September 2014; received in revised form 29 July 2015; accepted 30 July 2015

Abstract

Data of high frequency gravity wave propagation direction from globally distributed stations indicate a meridional preference of mesospheric gravity waves to be globally oriented toward the summer pole. This orientation is opposite to the mean residual circulation (from summer to winter pole) at mesospheric altitudes. We discuss here a number of dynamic mechanisms including filtering that may be responsible for the preferential wave orientation, and the effects of the gravity wave forcing imposed on the meridional flow due to dissipative waves. Using nightglow image data recorded in three distinct latitude stations, we have estimated the meridional wave drag (i.e, deceleration) of about -4.6 ± 0.2 m/s/day during the summer, and 3.8 ± 0.2 m/s/day during the winter, which is significant because the meridional flow has small magnitude. This is a component of dynamic forcing in the mesopause region, not heretofore recognized.

Keywords: Residual meridional circulation; Gravity waves; Wave drag; Nightglow

1. Introduction

The meridional residual circulation (MRC) is the result of the inter-hemisphere thermal gradient caused by a middle atmosphere out of radiative balance due to mechanical wave forcing (Houghton, 1978; Solomon et al., 1987). Postulated by Brewer (1949), the MRC explains the high concentration of ozone and water vapor at high latitudes even the production is larger at low latitude due to the higher solar illumination.

In the lower atmosphere, the meridional circulation is composed of two circulation cells below the tropopause, with upwelling (downwelling) of air parcels at the equator (poles), and travel from equator to pole to close the loop. Near the mesopause, the MRC is a single cell structure, presenting air upwelling in the summer pole and downwelling in the winter pole, and a residual flow from pole to pole at those altitudes closing the circuit (e.g., Yue and Liu, 2010). The MRC has mean absolute magnitude of 5–25 m/s during solstices, which follows from climatologies obtained from satellite measurements (McLandress et al., 1996). Also, the Zhu et al. (1997) model showed MRC magnitudes of ∼25 m/s around 92 km, with maximum in the summer mesopause.

The dominant mechanism driving the atmosphere out of radiative equilibrium is the dissipation and breaking of gravity waves (GW). The GW momentum deposition (i.e., the flux divergence, wave acceleration, or wave drag) could reach ∼100 m/s/day, as estimated through rocket observations (Lindzen, 1981). The influence of gravity waves on the background zonal flow in the stratosphere is relatively well understood, and has been parameterized

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http://dx.doi.org/10.1016/j.asr.2015.07.040
0273-1177/

Please cite this article in press as: Vargas, F., et al. Evidence of high frequency gravity wave forcing on the meridional residual circulation at the mesopause region. Adv. Space Res. (2015), http://dx.doi.org/10.1016/j.asr.2015.07.040

(e.g.,Holton and Zhu, 1984; Zhu et al., 2014), and included in Global Circulation Models (GCM) such as the Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model (TIME-GCM). The model proposed by Zhu et al. (1997) is consistent with meridional velocities of 20–30 m/s measured by the Upper Atmosphere Research Satellite (UARS), and supports a mesosphere forced by breaking/dissipating gravity waves. However, a fine-tuning of the parameterization schemes is still an important subject for the modeling community (e.g.,Hoffmann et al., 2010). In fact, there is evidence of significant departures from modeled winds, predicted by current Global Circulation Models. For example, the meridional circulation strength estimated by TIME-GCM is inconsistent with observations of the fast transport of water plumes released during rocket lunches (Yue and Liu, 2010), which presented rapid displacements at velocities of 35–40 m/s. As observed by Yue and Liu (2010), tides and planetary waves can be responsible for departures from the means at those altitudes.

It is now well understood that high frequency (HF) gravity waves (period $\lesssim 1$ h) propagating from the lower atmosphere into the mesosphere carry significant momentum (e.g., Zhang et al., 2014), and, when damped, transfer that momentum to the mean flow. Also it is well understood that the strong zonal circulation filters the waves, as shown in very early dynamic studies. The strong stratospheric westerlies in the winter remove the westerly propagating waves preventing them from reaching the mesosphere. The opposite is true for the summer, when the strong stratospheric easterlies transmit only the westerly propagating waves into the mesosphere.

We have observational evidence of HF waves observed in the mesospheric airglow layers from a number of stations around the globe. These waves have been studied and segregated here into their directional trends for summer, equinox, and winter. The data set shows, however, that the meridional component of waves reaching the mesopause region have a preponderant orientation toward the summer pole. Note there is no strong filter for the meridional waves in the stratospheric wind pattern.

In this paper, we discuss how HF gravity waves observed in nightglow images show a persistent horizontal wave propagation into the MRC, and which dynamic mechanisms are the causes of such GW orientation. We also discuss how GW would drive the meridional flow around the mesosphere and lower thermosphere altitudes. Finally, we estimate GW forcing magnitude on the meridional flow by using nightglow image data recorded at three stations (two in Brazil and one in Chile). The objective of this paper is to bring our conclusions to the attention of the upper atmospheric dynamics community and to discuss the likely effects which are not currently contained in dynamic models to the circulation. This meridional high frequency gravity wave effect is less recognized than that in the zonal direction, but not less important, and requires further investigation.

2. The Meridional Component Vector of GW at the Mesosphere

Several studies have addressed the directionality of the gravity wave field observed through nightglow imaging. Table 1 presents several references used to access the directionality of high frequency GW in nightglow images. The data was taken from stations having seasonally relevant data. The references are sorted by low, mid, and high latitude. The emissions recorded in a particular location, the date of the observations, and the number of nights in which measurements were made under clear observation conditions are also given. The station index posted in column nine is defined as the number of observational nights in each site divided by the number of months necessary to perform those measurements under clear skies and good weather conditions.

We have arranged the papers as long, medium, or short term with the idea of ranking them by their statistical strength, and showed the predominant meridional component vector of GW observed in each of them. Short term studies present a nightglow dataset of less than 6 months long, and medium term studies have a dataset of 6 to 18 months, respectively. Long-term climatologies are those with more than 18 months of image data.

Fig. 1 shows a world map and the geographical distribution of stations around the globe as given in Table 1. Fig. 1(a) refers to the northern hemisphere winter, and Fig. 1(b) refers to the northern hemisphere summer. The net horizontal orientation of the wave field is represented by the zonal and meridional arrow components placed at the geographical position of each station. The size of each arrow is proportional to the percentage of net wave field propagating in a specific direction for the time length of a given study. For simplicity, three arrow lengths were defined: arrows having three length units represent a large number of GW moving in that direction (>70%); two length unit arrows represent 30% to 70% of the waves moving in the given direction; one length unit arrows express less than 30% waves with that orientation. No arrow on a given station indicates no data available there. Only solstice data is present in Fig. 1.

Notice that long-term climatologies obtained from several stations have provided good understanding of spatial and temporal scales of GW as well as their seasonal propagation direction to the summer pole. Short and mid term observation campaigns also support this prevalent GW motion.

Fig. 2 presents a meridional cross-section (latitude vs. altitude) of the (a) zonal and (b) meridional background wind for June of 2009 taken from the Horizontal Wind Model 93 (HWM93) (Hedin et al., 1991), corresponding to the northern hemisphere summer. The maximum zonal velocity is ~75 m/s at the stratosphere. The stratospheric zonal wind is westward in the northern hemisphere summer, and eastward in the southern hemisphere (Fig. 2(a)). On the other hand, the meridional wind is much

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