Evidence of High Frequency Gravity Wave Forcing on the Meridional Residual Circulation at the Mesopause Region

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Abstract

Data of high frequency gravity wave propagation direction from globally distributed stations indicate a meridional preference for the mesospheric gravity waves to be globally oriented toward the summer pole. This is opposite to the mean residual circulation (summer to winter) at mesospheric altitudes. We discuss here a number of dynamic considerations including filtering that may be responsible for the preferential wave orientation, and the effect 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;

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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 (e.g., Holton and Zhu, 1984; Zhu et al., 2010), 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 $\lesssim 1$ hour) 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 into their directional trends for summer 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 also discuss 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 with 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 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 sorted the papers as long, medium, or short term studies with the idea of ranking each study by its 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. 1a refers to the northern hemisphere winter, and Fig. 1b 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 that no data was 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. 2a). On the other hand, the meridional wind is much weaker than the zonal wind throughout 0-100 km range, reaching its maximum of ~ -30 m/s around mid latitudes at mesospheric altitudes (Fig. 2b).

During summer solstices, we observe an easterly flow, and a westerly flow during the winter solstice. It is well known the zonal flow filters out a portion of the GW spectrum propagating from the troposphere to the mesosphere. Thus, the angular spectrum of GW has a dominant anisotropy during solstices that depends basically on the season and is opposite to the stratospheric wind. The zonal component vector of GW in Fig. 1 is consistent with zonal wind filtering of GW in the stratosphere once the zonal wave motion is preferentially westward in the northern winter, and eastward in the southern summer for most sites. This zonal filtering condition breaks down at some specific locations (e.g. Kototabang, Indonesia), most likely due to local wave sources nearby (Suzuki et al., 2009b), but generally holds true for most of the stations. During the equinoxes, the zonal wind is weaker at the stratosphere, and the GW filtering is not as effective as during the solstices, resulting in a more isotropic wave field observed at higher altitudes.

The meridional component vector of GW in Fig. 1 is mostly poleward (equatorward) during the summer (winter), and equatorward (poleward) during the winter (summer) in the northern (southern) hemisphere. Notice the remarkable feature of the GW meridional component vector (vertical arrows) showing a persistent orientation to the summer pole opposite to the direction of the MRC (from summer to winter). This characteristic is observed in both northern hemisphere winter and summer. The mechanisms driving the meridional component vector of GW to the summer pole must be ubiquitous and have not been shown in a global picture as that presented here.

Assuming that tropospheric sources are isotropic in the sense that generated waves are radiated to any possible direction, the meridional component vector of GW should be then equally partitioned in equatorward and poleward oriented waves. However, Fig 1 shows clearly that the orientation of the wave field from the winter to the summer pole is widely dominant. Only during the summer in Calgary, Tirunelveli, and Tanjugsari we observe a departure from the dominant meridional wave orientation. As discussed in the studies using image data from those three stations, the peculiar wave orientation was caused by local convective sources nearby those specific observatories. We discuss next what feasible mechanisms would be driving that GW orientation characteristic.

3. Causes of the Meridional Orientation of GW

The relative position of convective wave sources to the observation stations would give clues about the preferential meridional wave orientation. Fig. 3 shows a global picture of the lightning activity associated with tropospheric convection forcing of GW from cumulonimbus clouds during the winter and summer of 1999 obtained by the Optical Transient Detector (OTD) satellite developed by the National Aeronautics and Space Administration (NASA). The picture is also representative of the lightning activity for the years of 1995, 1996, 1997, 1998 and 1999 for both winter and summer, being a proxy of gravity wave convective sources throughout the globe (e.g., [Fritts et al., 2006](#)). The lightning activity is larger during the summer, in both hemispheres.

Convective sources are likely the most effective sources of waves that would propagate up to the mesosphere ([Fritts et al., 2006](#)). If the radiated waves became trapped in their vertical path, then they would be able to travel large horizontal distances, and then be detectable in stations far away from the original source (e.g., [Walterscheid et al., 1999](#); [Hecht et al., 2004](#)). However, because convection radiates GW isotropically, some other mechanism must be acting in order to explain the highly dominant wave propagation to the summer pole from low latitude sources. That is, the relative positioning of wave sources relative to the observation stations can not explain the GW preferential orientation to the summer pole.

Waves propagating opposite to the summer pole could somehow be removed from the wave field by filtering due to the meridional wind in a similar fashion to that of the zonal wind. However, the meridional wind is weak, having significant magnitude (~ 30 m/s) only at mid latitudes around 90-100 km height (Fig. 2b). This way, the meridional wind would not be an effectively filter waves because high frequency GW observed in airglow images usually present large phase velocities ($\gtrsim 40$ m/s). The meridional wind offers a path to GW into the MRC because it is weak and not capable of blocking the waves in their way by filtering. Consequently, it is unlikely to be responsible for the persistent meridional direction of the GW.

Above the stratosphere, tidal wave modes have magnitudes that would be consistent with GW filtering in the mesosphere, giving a feasible mechanism that could explain the meridional motion of GW around the globe. However, tidal phases and amplitudes would have to be highly homogeneous around the globe to permit only gravity waves moving toward the summer pole to

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9 survive to this filtering mechanism, which is also very unlikely. Also, from
10 our image data set, another evidence against tidal filtering is based on the
11 fact that GW observed simultaneously in images of different nightglow layers
12 frequently present very similar orientation. If tidal winds would be filtering
13 waves between layers separated in altitude, then the wave field orientation
14 would not have similar orientation characteristics.
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16 Likewise, it has been anticipated from gravity wave studies supporting the
17 residual circulation that zonally directed waves emerging from the stratos-
18 pheric filtering reach the mesosphere, applying zonal stress when they break
19 or dissipate. Examination of the angular pattern of the wave direction clima-
20 tology from studies by [Tang et al. \(2005\)](#) and [Li et al. \(2011b\)](#) would suggest
21 that the propagation direction was prevalent in the middle stratosphere, by
22 the time the waves have reached the mesopause, the angular spectrum would
23 be rotated by $\sim 60^\circ$ clockwise for the respective season (and hemisphere). We
24 have also considered how the horizontal wind shear could impose rotation to
25 the parcel and verified that it would cause a clockwise rotation of phase
26 fronts as well. Also, the shear magnitude is too small to induce this kind of
27 rotation for HF waves, whose transit exposure time to the shear would be on
28 the order of an hour through the middle atmosphere.
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30 The most likely explanation for the meridional wave orientation is that
31 given by [Walterscheid et al. \(1999\)](#). The wave propagation direction is in-
32 fluenced by the mean flow and by the temperature structure of the meso-
33 sphere. In fact, [Walterscheid et al. \(1999\)](#) show substantial evidence that
34 quasi-monochromatic GW are most likely trapped in the Lower Thermo-
35 sphere Duct (LTD), being able to travel long distances. The LTD structure
36 coupled with the zonal wind regime during solstices would create good condi-
37 tions for poleward (equatorward) oriented waves during the summer (winter)
38 to propagate, while suppressing waves having other orientations. In addition,
39 the penetration conditions created by the LTD would be global and consis-
40 tent with the winter/summer altitude of the LTD during those seasons.
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42 In a sense of wave influence, the new consideration is that indeed, the
43 zonal component vector of GW reaching the mesopause region imposes a
44 stress, which coupled with the Coriolis force, sets up the residual circulation
45 (summer to winter flow), and the residual circulation in turn, offers a channel
46 for the meridional propagating waves to, in turn, apply a meridional stress
47 to slow down that meridional flow.
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4. Estimation of the Meridional Drag due to Breaking/Dissipating GW

Because dissipative waves are dominant in the mesosphere and low thermosphere region (e.g., [Tang et al., 2005](#)), they are expected to force the background flow, which results in deceleration. We have measured the magnitude of the high frequency GW drag based on image analysis and GW parameter estimation given in [Liu and Swenson \(2003\)](#); [Tang et al. \(2005\)](#); [Vargas et al. \(2007, 2009\)](#). Evidence of the wave influence in the mesosphere and lower thermosphere region is associated, for example, with the downward wave-induced fluxes as measured by [Gardner and Liu \(2010\)](#).

We have airglow image data of the OH and the $O(^1S)$ emissions obtained in three stations: Cariri, Brazil ($7^\circ S$) (two years of data), Cachoeira Paulista, Brazil ($23^\circ S$) (four years of data), and Cerro Pachon, Chile ($30^\circ S$) (two years of data). The wave flux divergence (or wave drag magnitude) is essentially given by:

$$D = -\frac{1}{\bar{\rho}} \frac{\partial (\bar{\rho} F)}{\partial z} = -\frac{1}{\bar{\rho}} \left(\frac{\partial \bar{\rho}}{\partial z} F + \frac{\partial F}{\partial z} \bar{\rho} \right) \quad (1)$$

where $\bar{\rho}$ is the background density and F the momentum flux of a given wave event (see [Vargas et al. \(2007\)](#) and [Vargas et al. \(2009\)](#) for further details of D estimation). In this specific study, we have calculated D between the OH (87km) and $O(^1S)$ (96km) layers only because these layers hardly overlap in altitude.

Estimations of D for the available dataset are presented in Fig. 4 for all three stations. The charts are sorted from lower (top) to higher (bottom) latitude. Each chart presents the flux divergence vs. wave orientation for each season, and shows explicitly the wave preferential meridional component oriented from winter to summer pole. Waves propagating eastward, northward, westward, and southward have orientation of 0° , 90° , 180° , and 270° , respectively. The arrows have units of m/s/hour. Summer data in Cachoeira Paulista is sparser due to the rainy season occurring from December to January at that location. The higher wave activity density at Cerro Pachon is a result of 300 days of cloudless skies per year.

To summarize the results of Fig. 4, the averaged wave drag and its uncertainty is presented in Table 2 for summer, winter, and equinox, respectively. The values in Table 2 refer only to the meridional component vector of GW (northward). Negative (positive) values indicate southward (northward)

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9 wave drag. Large uncertainty in D estimations ($> 100\%$) are not shown in
10 Table 2.

11 During the equinoxes, we have found that the mean drag imposed by GW
12 is very small once the angular spectrum of GW is more isotropic. On the
13 other hand, the mean drag is 3.8 ± 0.2 (-4.6 ± 0.2) m/s/day during the winter
14 (summer). This is clearly a result of the wave preferential orientation (from
15 the winter to the summer pole) during those seasons. This GW drag is large
16 enough and could possibly counterbalance (or even reverse) the MRC, being
17 this scenario globally valid.
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22 5. Summary

23 We have shown in this paper evidence of a preferential propagation direc-
24 tion of high frequency gravity waves in the mesopause region to the summer
25 pole and into the residual meridional circulation as global trend, in both
26 hemispheres. This effect is real and has been shown in nightglow image data
27 collected in several stations distributed globally during more than 10 years.

28 The mechanism driving the directionality of gravity waves to the sum-
29 mer pole is not well understood. Likely the meridional winds at lower alti-
30 tudes offer a propagation path to gravity waves into the meridional residual
31 circulation. The gravity waves, in turn, apply stress to limit that meridio-
32 nal summer-winter wind circulation. We have estimated the wave drag as
33 -4.6 ± 0.2 m/s/day during the summer and 3.8 ± 0.2 m/s/day during the winter
34 from nightglow image data of three observation stations in South America.

35 Because the magnitude of the MRC is small (5-25 m/s) and oriented to
36 the winter hemisphere, the estimated gravity wave drag would possibly offset
37 (perhaps reverse) the mean meridional wind, or contribute to the return
38 circulation at higher altitudes, in a similar fashion that occurs in the zonal
39 direction. In case the meridional wave drag magnitude is nonzero globally, we
40 also suggest a larger magnitude of the residual meridional circulation than
41 that reported in the literature. Therefore, it is necessary to compare the
42 parameterized GW forcing with the observations in order to obtain reliable
43 estimations of the global circulation in the mesosphere and lower thermosphere
44 region.
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Figure 1: (a) GW drag direction around the globe during the northern winter (southern summer) (b) GW drag direction around the globe during the northern summer (southern winter).

Figure 2: Altitude vs. latitude cross-section of the (a) zonal and (b) meridional background wind provide by the Horizontal Wind Model 93 (HWM93) (Hedin et al., 1991). The following inputs were used in the model run: year: 2009, doy: 180 (June 29), latitude: 30.3°S, longitude: 70.7°W, local solar time: 20.2 h (00:00 UT), F107: 150, and Ap: 4)

Figure 3: Lightning activity for the northern (a) winter and (b) summer in 1999 provided by the Optical Transient Detector (OTD) satellite, launched by the National Aeronautics and Space Administration, NASA.

Figure 4: Flux Divergence vs. Propagation Direction of GW observed between OH and $O(1S)$ layers in (a) Cariri, (b) Cachoeira Paulista, and (c) Cerro Pachon. Arrows have units of m/s/hour.

Table 1: List of observatories around the globe that have reported gravity wave activity in the mesosphere region via nightglow imagery. Nightglow layer centroid altitudes are: OH: 87 km, Na: 90 km, O₂(b): 94 km, and O(¹S): 96 km.

	Site	GLat °	GLon °	Emissions	Year	nights #	Station Index	Term	Refs
HL	Resolute Bay	CAN 74.7	-94.9	Na	2005-2006	137	5.7	mid	Suzuki et al. (2009a)
	Esrang	SWE 67.9	21.1	OH O ₂ (b) O(¹ S) Na	2003	5	0.4	short	Nielsen et al. (2006)
	Calgary	CAN 51.0	-114.0	OH	1988-1990	36	1.4	short	Giers et al. (1997)
ML	Rikubetsu	JPN 43.5	143.8	OH O(¹ S)	1998-1999	–	–	mid	Ejiri et al. (2003)
	Millstone Hill	USA 42.6	-71.5	OH O(¹ S) Na	1998	12	1.0	short	Smith et al. (2000)
	Yucca Ridge Field	USA 40.7	-104.9	OH	2003-2008	218	3.6	long	Dou et al. (2010)
	XingLong	CHN 40.2	117.4	OH	2009	19	1.6	mid	Li et al. (2011a)
	Urbana	USA 40.0	-88.0	OH O ₂ (b)	1996-1997	–	–	long	Hecht et al. (2001)
	Mountain Research	USA 40.0	-105.6	OH	1988	20	1.7	short	Taylor et al. (1993)
	Starfire Optical	USA 35.0	-107.0	OH	1998-2000	32	0.9	short	Tang et al. (2002)
	Shigaraki	JPN 35.0	136.0	OH	1996-1998	161	4.5	mid	Higashikawa et al. (1999)
	Maui	USA 20.7	-156.3	OH	2002-2007	513	8.6	long	Li et al. (2011b)
	Arecibo Obs.	PRI 18.3	-66.7	OH O(¹ S)	1993	10	0.8	short	Taylor and Garcia (1995)
LL	Tirunelveli	IND 8.7	77.8	OH O(¹ S) Na	2007	38	3.2	mid	Narayanan and Gurubaran (2013)
	Kototabang	IDN -0.2	100.3	OH	2002-2005	–	–	long	Suzuki et al. (2009b)
	Alcantara	BRA -2.3	-44.5	OH O(¹ S) Na	1994	25	2.1	short	Taylor et al. (1997)
	Tanjung Sari	IDN -6.9	107.9	OH	2001-2002	238	9.9	mid	Nakamura et al. (2003)
	Cariri	BRA -7.0	-36.0	OH O ₂ (b) O(¹ S)	2004-2005	78	3.3	long	Vargas (2007)
	Darwin	AUS -12.4	131.0	OH O(¹ S)	2001-2002	44	1.8	mid	Suzuki et al. (2004)
	Katherine	AUS -14.5	132.3	OH	2001	10	0.8	short	Pautet et al. (2005)
	Wyndham	AUS 15.5	128.1	OH O(¹ S)	2001	10	0.8	short	Pautet et al. (2005)
	Cachoeira Paulista	BRA -22.7	-45.0	OH O ₂ (b) O(¹ S)	1999-2005	127	3.5	long	Vargas (2007)
	Alice Springs	AUS -23.4	133.5	OH O ₂ (b)	2001	6	0.5	short	Hecht et al. (2004)
	Andes Lidar Obs.	CHL -30.3	-70.7	OH	2009	144	12.0	long	this work
	Adelaide	AUS -35.0	138.0	OH O ₂ (b)	1995-1996	50	2.1	mid	Ding et al. (2004)
	Brazilian Antarctic	BRA -62.6	-58.4	OH	2007	40	3.3	short	Bageston (2009)
	Rothera	USA -67.0	-68.0	Na	2002-2003	58	2.4	short	Espy et al. (2006)
	Halley Bay	USA -76.0	-27.0	Na	2000-2001	112	4.7	mid	Espy et al. (2004)

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Table 2: Meridional component vector of GW drag (m/s/day) from nightglow imagery. High uncertainty data were omitted.

Station	Summer	Winter	Equinox
Cariri	-0.7 ± 0.4	10.0 ± 1.7	1.9 ± 0.6
Cachoeira Paulista	-	16.1 ± 1.6	-
Cerro Pachon	-6.9 ± 0.3	3.5 ± 0.2	-
Weighted Mean	-4.6 ± 0.2	3.8 ± 0.2	1.9 ± 0.6