High Frequency Gravity Waves Observed in OH airglow at Starfire Optical Range, NM: Seasonal Variations in Momentum Flux

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[1] Airglow imager and Na wind/temperature lidar measurements at Starfire Optical Range, New Mexico (35°N, 107°W) are used to estimate the seasonal variation of the vertical fluxes of horizontal momentum carried by high frequency Atmospheric Gravity Waves (AGWs). The cross-correlation coefficients between the vertical and horizontal wind perturbations were calculated from the OH airglow imager data collected during 32 nights in 1998, 1999 and 2000. The RMS wind velocities were deduced from the lidar measurements. The combined information was used to estimate the upper limit of the momentum flux. The meridional component of the vertical flux of horizontal momentum was observed to be towards the summer pole. The zonal component had westward preference in winter and weak preference in summer. The unanticipated large meridional component may act to regulate the summer to winter circulation in the mesosphere. INDEX TERMS: 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 0310 Atmospheric Composition and Structure: Airglow and aurora; 3360 Meteorology and Atmospheric Dynamics: Remote sensing. Citation: Tang, J., A. Z. Liu, and G. R. Swenson, High frequency gravity waves observed in OH airglow at Starfire Optical Range, NM: Seasonal variations in momentum flux, Geophys. Res. Lett., 29(20), 1966, doi:10.1029/2002GL015794, 2002.

1. Introduction

[2] Atmospheric gravity waves (AGWs) play important roles in the dynamics and thermal balance of the mesosphere [Fritts and van Zandt, 1993; Roble and Ridley, 1994; Hamilton, 1996; McLandress, 1998]. In order to refine the global circulation models (GCMs) [Fritts and van Zandt, 1993; Fritts and Lu, 1993; for example], information about the seasonal and latitudinal variation of AGW momentum flux is needed. In the mesopause region, the horizontal momentum is carried primarily by AGWs with periods shorter than 1 hour. Vincent [1984] found that roughly two-thirds of the momentum was carried by waves with periods shorter than 45 minutes. Waves with vertical wavelengths greater than 12 km are readily observed in the airglow images [Swenson and Gardner, 1998]. These waves typically have short horizontal wavelengths and large phase speeds (T < 60 min, λ_v > 12 km, λ_h < 150 km, and C_i > 40 m/s) [Taylor et al., 1995; Swenson et al., 2000].

[3] In this study, all-sky image sequences taken from June 1998 to October 2000 were analyzed for their spectral content using the image processing procedures described by Coble et al. [1998] with additional refinement of the star filtering method described by Tang et al. [2002]. The unambiguous horizontal wave number spectrum was used to calculate the wavelength and azimuth distribution of AGW energy propagating through the mesopause region. By applying the techniques of Gardner et al. [1999] to this spectrum, estimates of the vertical flux of horizontal momentum were obtained. The results were then sorted for summer (Mar. 21–Sept. 22) and winter (Sept. 23–Mar. 20) for comparison.

2. Data Processing

[4] Between 1998 and 2000, airglow emissions were measured using an all-sky imager with a broad-band OH filter (750–900 nm) at USAF Starfire Optical Range (SOR) near Albuquerque, New Mexico. At the same location, a Na lidar coupled with a 3.5m diameter steerable telescope was used to make wind and temperature observations at SOR. Figure 1 gives the annual sampling distribution of imager observation nights. Wind data collected by the lidar was available for all the nights of imager data in 1998, 1999 and several nights in 2000.

[5] The data set in each night with a clear sky was processed with the following procedure. The images were first flat-fielded to correct for the response introduced by the fish eye lens and the van Rhijn effect [Coble et al., 1998]. The stars were then removed from the flat-fielded images using the gradient-based edge detection technique described by Tang et al. [2002]. This technique was shown to be more effective for star removing than conventional algorithms [e.g., Garcia et al., 1997]. After the stars were removed, the star-free images were interpolated to a rectilinear grid of atmospheric coordinates. We chose a 150 km by 150 km field of view with a spatial resolution of 0.59 km. Finally, the images were detrended by fitting a plane to each interpolated relative perturbation image and then subtracting the brightness trend defined by the plane. The reason for this step is to remove the influence introduced by large horizontal scale waves.

[6] Once the raw images were processed, we calculated the three-dimensional Fourier spectrum of the airglow perturbations. Before the fast Fourier transform (FFT) technique was applied, the finite spatial and temporal extent of the data set had to be considered. To preserve the high-frequency content of the data, the images were first passed through the spatial and temporal whitening filters described by Coble et al. [1998]. Then non-rectangular spatial and temporal windows were applied to reduce the side lobes caused by data truncation. These steps provided assurance...
that the three-dimensional FFT created thereafter, is a proper spectral estimate of the perturbations in the mean OH airglow intensity, a proxy for the AGW spectrum.

[7] The unambiguous two-dimensional horizontal wave number spectrum describes the distribution of gravity-wave energy as a function of horizontal scale and propagation direction. The computed spectrum included the effects of waves with horizontal wavelengths between 2.4 km and 150 km and observed periods between 4 minutes and 2 hours. The spectrum was computed by integrating the re-colored 3-D spectrum over the frequency range. The angular spectrum showed the distribution of wave energy as a function of propagation direction and was calculated by integrating the 2-D spectrum over the magnitude of the horizontal wave number from \(2\pi/(150 \text{ km})\) to \(2\pi/(2.4 \text{ km})\) [Coble et al., 1998]. Using the angular spectra, the relative OH intensity variance was calculated as a function of azimuth angle [Coble et al., 1998]. Gardner et al. [1999] related the azimuth distribution of the relative OH intensity variance to the cross-correlation coefficients between the perturbations of horizontal and vertical winds, i.e., \(\left\langle w'v'\right\rangle w'_{rms}u'_{rms}\) and \(\left\langle w'v'\right\rangle w'_{rms}v'_{rms}\), respectively (Eqns. 26 and 27 in Gardner et al. [1999]).

\[
\begin{align*}
\left\langle w'v'\right\rangle &= G \cdot \frac{2}{\pi} \int_0^{\pi/2} d\phi \frac{\left\langle f_{OH}(\phi) f_{OH}(\phi)\right\rangle}{f_{OH}} \sin \phi \\
\left\langle w'v'\right\rangle &= G \cdot \frac{2}{\pi} \int_0^{\pi/2} d\phi \frac{\left\langle f_{OH}(\phi) f_{OH}(\phi)\right\rangle}{f_{OH}} \cos \phi
\end{align*}
\]

Where \(w'_{rms}, u'_{rms}\), and \(v'_{rms}\) are RMS values of horizontal, zonal and meridional wind perturbations, \(f'_{OH}\) and \(I_{OH}\) are the relative perturbations and the mean value of the OH emission intensity, \(\phi\) is the azimuth angle and \(G\) is the range of the cross-correlation coefficient. For the calculation of uncertainties of the zonal and meridional correlation coefficients, refer to the appendix in Gardner et al. [1999]. Once \(w'_{rms}, u'_{rms}\), and \(v'_{rms}\) are known, the momentum fluxes \(\left\langle w'v'\right\rangle\) and \(\left\langle w'v'\right\rangle\) can be calculated based on (1) and (2). \(w'_{rms}, u'_{rms}\), and \(v'_{rms}\) for the OH layer altitudes were computed using the lidar wind data at 87 km from zenith and off-zenith measurements [Gardner et al., 1998]. For the nights when lidar wind data were available, RMS values of horizontal and vertical wind perturbations \(w'_{rms}, u'_{rms}\), and \(v'_{rms}\) of the nights were used together with the correlation coefficients to calculate the momentum fluxes \(\left\langle w'v'\right\rangle\) and \(\left\langle w'v'\right\rangle\) [Vincent and Reid, 1983]. For the nights without the lidar wind data, we used the average summer or winter values of \(w'_{rms}, u'_{rms}\), and \(v'_{rms}\) for momentum fluxes calculation. This is justified by the small standard deviation of the wind variances (see Table 1).

### 3. Experimental Results

[8] Thirty-two nights of images were processed from the summer and winter SOR data sets of 1998, 1999 and 2000. We calculated estimates for the vertical flux of horizontal momentum for each night using the method described above. As an example, the unambiguous two-dimensional horizontal wave number spectrum and the angular spectrum for Jan. 4, 2000 are shown in Figure 2. The 2-D spectrum indicates that most of the energy is concentrated in waves with horizontal wave numbers less than 1/30 cycles/km, which correspond to waves with horizontal wavelengths greater than 30 km. The angular spectrum indicates that on this night more wave energy propagated westward than eastward.

[9] In Figures 3 and 4, scatter plots of momentum fluxes are shown with winter and summer data separated. The nights with and without wind data are distinguished as described in the figure captions. The direction of nightly averaged momentum flux is dictated by the correlation coefficient as stated in Section 2.

[10] Figure 3 shows that during winter, the net meridional wave transport is directed southward. The average value of meridional momentum flux for winter is \(-11.95 \text{ m}^2\text{s}^{-2}\). Comparatively, during summer, as shown in Figure 4, the net meridional wave transport is mainly northward. Its average value is 13.70 \text{ m}^2\text{s}^{-2}\). In winter, the zonal momentum flux is westward on almost all the nights. Its average is \(-19.79 \text{ m}^2\text{s}^{-2}\). In summer, the zonal momentum flux has a weak westward component with an average value of \(-2.37 \text{ m}^2\text{s}^{-2}\). These values are comparable to the average results reported by Gardner et al. [1999] calculated from 5 nights in 1995, which are \(-11.9 \text{ m}^2\text{s}^{-2}\) in zonal direction and \(-3.76 \text{ m}^2\text{s}^{-2}\) in meridional direction. Gavrilov et al. [2000] estimated the momentum flux for waves with relatively long horizontal wavelength (>60 km) and short vertical wavelength (6–10 km) between 70–80 km, using measurements made with MU radar. Their values are much smaller than we reported here. This indicates that the high frequency

| Table 1. RMS Winds Observed at 87 km by the Na Wind/Temperature Lidar |
|-----------------------|-------|-------|-------|-------|
|                      | Winter |       | Summer |       |
| Zonal (m/s)          | 22.23  | 5.43  | 20.74  | 3.80  |
| Meridional (m/s)     | 22.35  | 5.30  | 21.34  | 3.83  |
| Vertical (m/s)       | 3.05   | 0.95  | 2.96   | 0.66  |
AGWs with long vertical wavelength observed with airglow imagers are the dominant source of momentum flux.

4. Discussion

[11] The momentum fluxes calculated above include all waves that are detectable by the airglow imager ($\lambda_h < 150$ km). Some waves, however, may be ducted waves that have no contribution to vertical flux of horizontal momentum [Fritts, 2000]. Isler et al. [1997] reported that waves with horizontal wavelength less than 15 km are likely to be ducted. Swenson et al. [2000] found that waves with $\lambda_h < 20$ km may be near ducting limit. Smith et al. [2000] reported 55% of wave events with mean horizontal wavelength $21 \pm 7$ km were evanescent. To evaluate the effect of waves with small horizontal wavelength, we compared results that include and exclude waves with horizontal wavelengths shorter than 30 km and found less than 10% difference in the correlation coefficients. Therefore the spatial content less than 30 km is insignificant to momentum flux calculation in these observations.

[12] Using MU radar, Gavrilov et al. [1996] detected that in the layer from 70 to 80 km the mean portions of gravity waves with upward energy flux were 49–56% at Shigaraki, Japan (35°N, 136°E). Reisin and Scheer [2001] reported that 30% of the waves at 95 km and 40% at 87 km propagated downward from their measurements using spectrometer at El Leoncito (31.8°S, 69.2°W) and El Arenosillo (37.1°N, 6.7°W). According to Hu et al. [2002], 84.4% of the 700 monochromatic waves were propagating upwards extracted from lidar data collected at SOR between Jan. 1998 and May 2000. The result we presented, therefore, should be treated as an upper limit of the momentum flux. Further studies are required to establish the fraction of upward propagating waves. This topic is being pursued and the result will be reported in a separate paper.

[13] Recently, Nakamura et al. [2001] obtained the seasonal variations of propagation direction of gravity waves from OH imager data taken at Shigaraki, Japan (35°N, 136°E). The results they presented are similar to ours in the meridional preferences, i.e., poleward propagation in summer and equatorward in winter. As to the zonal direction, we found a westward preference in winter, the same as their result. However, we observed a very weak westward preference in summer, which is different from their clear eastward preference. Note that these two studies are from locations at nearly identical latitude, but ours are from western hemisphere and theirs from eastern hemisphere. Walterscheid et al. [1999] found the gravity waves mainly propagated northward in winter and southward in summer in the southern atmosphere at Adelaide.

AGWs with long vertical wavelength observed with airglow imagers are the dominant source of momentum flux.

Figure 2. Unambiguous 2-D power spectrum and angular spectrum of the OH airglow intensity for images taken during Jan. 4, 2000. The color bar in the 2-D spectrum is in logarithmic scale. The unit of the spectrum is (percentage/m)² representing (relative amplitude/wave number)². The angular spectrum is also in logarithmic scale. The unit in the spectrum is (percentage²/radian) representing (relative amplitude)²/radian.

Figure 3. Scatter plot showing nightly momentum flux estimates. The signs of momentum fluxes represent the direction of wave propagation. The data points show wave propagation exclusively in the SW. Winter in 1998, 1999 and 2000. The nights with wind data are presented in blue, without wind data are presented in yellow.
Figure 4. Same as Figure 3, except for summer. The wave propagation is dominated by northward direction. The nights with wind data are presented in red, without wind data are presented in yellow.

Australia (35°S, 138°E), i.e., the waves were primarily directed to the summer pole.

5. Summary

Using 32 nights of SOR all-sky imager OH data obtained during three years of observation, we have studied the seasonal variation in momentum flux of high frequency gravity waves. The direction and magnitude of momentum flux are derived using a 3-D spectral analysis technique that can unambiguously determine direction of wave propagation and cross-correlation between zonal and meridional directions from the sequence of images for each night.

The results indicate that the seasonal direction of momentum flux is predominately southwestward in winter and northwestward in summer in the northern hemisphere. Filtering in the lower atmosphere is well understood to allow transmission into the mesopause region of westward waves in winter and eastward in summer due to the prevailing winds in the stratosphere. However, major mysteries exist as to why there is dominance in the meridional direction for high frequency waves to propagate toward the summer pole.

The meridional momentum flux carried by these high frequency waves may have significant effects on the general circulation in the middle atmosphere. At these altitudes the meridional wind is from the summer to the winter pole. In this study we find that the meridional momentum flux has opposite direction to the meridional wind. The meridional wind is induced by dissipating waves that exert stress on the zonal wind and is decelerated by the meridional momentum flux.


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