Statistical characteristics of gravity waves observed by an all-sky imager at Darwin, Australia

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Received 7 November 2003; revised 3 March 2004; accepted 22 March 2004; published 26 August 2004.

[1] An all-sky airglow imager with a cooled charge-coupled device camera in place at Darwin (12.4°S, 131.0°E), Australia, since October 2001 has been used to obtain two-dimensional gravity wave images in the mesopause region. Using airglow images of the OI (557.7 nm, emission altitude ~96 km) and OH band (720–910 nm, ~86 km) emissions obtained for October 2001 to August 2002, we investigated the wavelengths, phase velocities, and propagation directions of gravity waves. Wave occurrence in OH images (60–90%) is higher than in OI images (30–70%) for all seasons. The waves have wavelengths of less than 90 km (peak: 30–50 km) and phase velocities of less than 90 m/s (peak: 30–60 m/s). Most of the waves propagate in the meridional direction, and the directionality strongly depends on the season. In winter, waves propagate both poleward and equatorward, while in summer almost all waves propagate poleward. An examination of airglow-imaging statistics at Adelaide (35°S, 138°E), Australia, obtained by Walterscheid et al. [1999], leads us to conclude that this clear directionality is caused by the location of the wave sources and by the wave ducting processes; that is, poleward waves in summer come from an equatorial convective source through a thermal duct structure. The effect of wind filtering on the waves is also discussed for zonal wave propagation.

INDEX TERMS: 0310 Atmospheric Composition and Structure: Airglow and aurora; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3384 Meteorology and Atmospheric Dynamics: Waves and tides; KEYWORDS: gravity wave, airglow, mesopause region

processes resulting from the mesospheric jet. However, Walterscheid et al. [1999] have reported that the gravity waves propagate mostly in the meridional direction at Adelaide. Walterscheid et al. [1999] have also said that the poleward waves in summer come from a convective source in the equatorial latitudes through a thermal duct.

[5] In this paper we investigate the properties of mesospheric gravity waves using the all-sky airglow imager at Darwin (12.4°S, 131.0°E), Australia, near the equator, where the convective wave source is active. We find that most of the waves propagate in meridional directions. On the basis of the observed seasonal variations in direction, we discuss the processes of wave propagation in the middle atmosphere.

2. Observation

[6] An all-sky airglow imager has been located at an ionosonde station of the IPS Radio and Space Services in Darwin, Australia, since October 2001. Since then it has been used to obtain two-dimensional airglow images in the lower thermosphere and the mesopause region. The imager is part of the Optical Mesosphere Thermosphere Imagers (OMTIs) [Shiokawa et al., 1999, 2000]. The imager has five interference filters on a wheel, a fish-eye lens with a field of view of 180°, and a cooled-CCD camera with 512 × 512 pixels. In the present study we use images of OI (557.7 nm, typical emission altitude ~96 km) and OH Meinel band (720–910 nm, ~86 km) emissions. Their integration times are 105 and 15 s for OI and OH, respectively. The imager takes 1 OI and 2 OH images every 6 min.

[7] Figure 1 shows examples of the OI and the OH images used in the analyses. To see the gravity wave structures clearly, we took the deviation of each image from a 1-hour running average. The top of the image is to the north, and left is to the east. The NE-SW structure seen in all images is the galaxy. In the OI images, NW-SE wave structures can be recognized with a wavelength of 30 km and a phase velocity of 42 m/s (propagating northeastward). In the OH images, east-west structures can be seen with a wavelength of 30 km and a phase velocity of 56 m/s (propagating southward). These wave parameters are taken by using a 10-km grid map on the all-sky airglow images, assuming that the airglow heights are 96 and 86 km for OI and OH, respectively.

3. Statistical Analysis

[8] Using the airglow images obtained at Darwin from October 2001 to August 2002, we investigated the wavelengths, phase velocities, and propagation directions of gravity waves in the mesopause region. These wave parameters were identified by using images of the deviation from the 1-hour running average with a gray scale of ±5%, like those shown in Figure 1. The minimum amplitude of waves identified by this method is ~1–2%.

[9] First, we checked the sky conditions at Darwin. Figure 2 shows the monthly sky condition at Darwin from October 2001 to August 2002. The curve with asterisks indicates the ratio of clear sky.

Figure 1. Examples of all-sky airglow images (deviation from 1-hour running average) observed at Darwin on 15 March 2002 at 1930–1942 UT (0430–0442 LT) (OI) and 1935–1947 UT (0435–0447 LT) (OH). The top and left of the images correspond to north and east, respectively. The northeast-southwest structure in the bottom left of all the images is the galaxy. NW-SE wave structures can be recognized in the OI images. East-west wave structures can be recognized in the OH images.

Figure 2. Monthly sky condition at Darwin from October 2001 to August 2002. The curve with asterisks indicates the ratio of clear sky.
images. Most of the wavelengths are less than 90 km, with a maximum at 30–50 km in both airglow images. Using OH and O2 airglow images at Adelaide, Walterscheid et al. [1999] reported that the horizontal wavelengths were a few tens of kilometers. Their wavelengths are also similar to our results. It should be noted that these figures do not always indicate the actual wavelength distribution of gravity waves in the mesopause region because the field of view of an all-sky imager used in the analyses is ~400 km in diameter in the mesopause region and because the images (deviation from 1-hour running average) we used are integrated over 105 s (OI) and 15 s (OH).

Figure 3. Occurrence rate of gravity waves observed by an all-sky airglow imager at Darwin for OI and OH from October 2001 to August 2002.

[12] Figure 5 shows distributions of the horizontal phase velocities in the OI and OH images. Most of the velocities are less than 90 m/s, with a peak at 30–60 m/s. The phase velocities reported by Ejiri et al. [2003] are similar to our results, with a peak at 30–60 m/s. Walterscheid et al. [1999] reported slightly higher velocities of ~50–80 m/s.

[13] To see the seasonal dependence of the wave parameters, we defined summer and winter as the four months of November-February and May-August, respectively, and spring and autumn as the two months of September-October and March-April, respectively, considering two major types of wind field in the mesosphere (summer and winter). Data from September were not available owing to instrument trouble. Figures 6a and 6b show seasonal variations in the averaged horizontal wavelengths and phase velocities for the two airglow emissions. The wavelengths observed in the OI images are larger than those in the OH images for all seasons. The wavelengths are ~40 km in spring, summer, and autumn. In winter they are larger than those seen in the other seasons by ~10 km for both emissions, although the statistical variance indicated by the vertical bars is large.

Figure 4. Horizontal wavelengths of gravity waves in OI and OH airglow images obtained at Darwin.

Figure 5. Horizontal phase velocities of gravity waves in OI and OH airglow images obtained at Darwin.

Figure 6. (a) Seasonally averaged horizontal wavelengths and (b) phase velocities for two airglow emissions.
The phase velocities are \( \sim 50 \) m/s and do not have recognizable differences between the two emissions. They are slightly larger in winter than in the other seasons, particularly for OI. Ejiri et al. [2003] also showed seasonal variations in the averaged horizontal wavelengths and phase velocities. Their results did not show large wavelengths and phase velocities in winter.

Figure 7 shows the seasonal dependence of the propagation direction of gravity waves. The radial scale indicates the fraction of waves propagating in each direction. Almost all waves in the OI and OH airglow images propagate in the meridional directions, especially in summer and winter. In summer, most of the waves propagate poleward (southward), with some expansion in the zonal direction (SE and SW). In winter, however, we observed as many equatorward components as poleward components, and the distribution is sharply in the meridional direction. For zonal directions the eastward component is more frequently observed in spring, autumn, and winter. In spring and autumn the distributions are similar to each other (southeastward is dominant). In the OH airglow images the northward component can be seen for both spring and autumn.

4. Discussion

4.1. Occurrence Rate

Figure 3 shows that the occurrence rate of gravity waves in the OH images is mostly higher than in the OI images. The averaged occurrence is 55 and 79% in OI and OH, respectively. This may be partly due to the difference in the integration time; that is, OI and OH images are obtained with an integration time of 105 and 15 s, respectively. Small-scale waves may be averaged out for longer integration times. For example, waves with a horizontal velocity of 50 m/s move 5 km in 105 s. Thus such waves with a wavelength of 10 km (5 km \( \times 2 \)) are averaged out by the 105-s integration. Another possibility is the difference in the height between the OI (\( \sim 96 \) km) and OH (\( \sim 86 \) km) emission layers. The upward propagating gravity wave may break between the two layers because of the thermal and dynamical structures around the mesopause region. The difference in intensities of OI and OH airglow emissions also may play a role. Typically, the OI and OH images have \( \sim 4000 \) and \( \sim 10,000 \) counts/pixel, respectively. Therefore the signal-to-noise ratio of the OH images is better than that of the OI images. Ejiri et al. [2003] also showed a high occurrence rate of more than 60%, but the occurrence rate of gravity waves in the OI images was slightly higher than in the OH images.

The seasonal variations of gravity wave occurrence in the OI and OH are 73 and 95% (spring), 48 and 81% (summer), 60 and 86% (autumn), and 60 and 80% (winter), respectively. In spring the occurrence rate shows a maximum for both OI and OH. However, spring contains only 1 month of data, October 2001. Wu and Killeen [1996] have reported that the activity of mesospheric gravity waves strongly depends on the season, with a peak in summer and much reduced activity in winter. However, such a prominent seasonal dependence is not recognized in the present results.

It is well known that Hector, which is a strong local convective source of gravity wave in the troposphere, frequently occurs near Darwin during October-December (K. Hamilton et al., The Darwin Area Wave Experiment (DAWEX) field campaign to study gravity wave generation and propagation, submitted to Journal of Geophysical Research, 2004). However, a significant increase in wave occurrence cannot be found in Figure 3. Gravity waves we observed may contain not only the waves generated by local convective sources near Darwin but also waves propagating a long distance. Since almost all waves had straight phase surfaces, most waves we observed may come from some distant sources.

4.2. Direction of Wave Propagation

As shown in Figure 7, almost all waves in both emissions propagate in the meridional direction, and the
Directionality shows strong seasonal variation. Walterscheid et al. [1999] have reported similar results for the quasi-monochromatic (QM) waves observed at Adelaide, Australia, at 35°S from 9 months of airglow imaging observations. The waves at Adelaide propagate mostly poleward in summer and equatorward in winter. They explain this strong seasonal dependence by using the idea of a thermal duct, which has a close relation to the height of the mesopause. The height of the mesopause is associated with a steep gradient in the Brunt-Väisälä frequency that causes the base of a lower thermospheric thermal duct to be located in the vicinity of the mesopause. The mesopause exists at two altitudes: a winter state near 100 km and a summer state near 88 km [She and von Zahn, 1998]. Walterscheid et al. [1999] interpreted the QM waves as being waves trapped in the lower thermosphere thermal duct structure over the Australian continent. Figure 6a shows that the wavelength in summer is slightly shorter than that in winter. This fact also favors wave ducting since the ducting waves have a large vertical wavelength and short horizontal wavelength.

In winter we observed both equatorward and poleward components at Darwin and only equatorward waves at Adelaide. The poleward component at Darwin may come from the equatorial convective source, which can work as a wave source even in winter. Nakamura et al. [2003] reported, on the basis of gravity wave observations in OH airglow images at Tanjungsari, Indonesia (6.9°S, 107.9°W), near the equator, that most of the gravity waves come from the equatorial convective source, which is identified by satellite cloud images.

The equatorward component was observed both at Darwin and Adelaide in winter. However, the equatorward waves observed at these two sites (separated by ~2300 km) are probably generated by different wave sources because the waves are not likely to be ducted in winter, when the mesopause exists above the airglow layer [Walterscheid et al., 1999]. We believe that the equatorward propagating waves at Darwin in winter are generated by another source located south of Darwin.

Figure 8. Zonal wind profiles for four seasons from URAP wind data [Swinbank and Ortland, 2003] averaged over November 1991 to December 1999. The contours indicate zonal wind velocities every 10 m/s in eastward (solid contour) and westward (dotted contour) directions. The vertical dashed lines indicate the latitude at Darwin.
Eastward waves are more frequently observed than westward waves in those seasons for both airglow emissions. This result may be explained by a background wind field, as discussed by Nakamura et al. [2001] and Ejiri et al. [2003]. Figure 8 shows the zonal wind profiles for four seasons (positive: eastward) taken from the seasonal averages of the UARS Reference Atmosphere Project (URAP) wind data from November 1991 to December 1999 [Swinbank and Ortland, 2003]. There is a westward wind in the upper mesosphere (70–100 km) over the vicinity of the equator in equinox seasons. The westward wind in the upper mesosphere (70–100 km) over the equator is weak and varies in time. This may be the reason that the eastward wind in the upper mesosphere has more influence than the lower and middle atmosphere on the gravity waves.

[23] It seems that there is also a strong directional preference toward the southeast for most seasons in OH and OI images. Tsuda et al. [2000] showed global distribution of potential energy per unit mass, which indicates the localized excitation of gravity waves, in the lower stratosphere in November-February (summer at Darwin). The distribution showed that the strong excitation of gravity waves exists over the Indonesian islands located north and northwest of Darwin. If this high wave activity is the major source of the gravity waves observed at Darwin, the strong southeastward preference can be observed.

5. Conclusion

[24] We have observed mesospheric gravity waves in OI and OH airglow images at Darwin from October 2001 to August 2002 using an all-sky imager. The observed characteristics are summarized as follows:

[25] 1. Occurrence rates of gravity waves in OI and OH images are ~30–70% and ~60–90%, respectively.
[26] 2. The horizontal wavelengths are mostly less than 90 km, with a peak at ~30–50 km.
[27] 3. The horizontal phase velocities are mostly less than 90 m/s, with a peak at ~30–60 m/s.
[28] 4. Observed gravity waves propagate mainly in the meridional direction. Almost all waves propagate poleward in summer, while both equatorward and poleward waves are observed in winter.
[29] 5. Eastward waves are more frequently observed than westward waves in spring, autumn, and winter.

[30] The fact that the waves propagate poleward in summer is consistent with the thermal ducting of gravity waves, as suggested by Walterscheid et al. [1999]. The equatorward waves in winter may imply that an additional source exists at latitudes between Darwin and Adelaide. The eastward preference in spring and autumn may be due to the wind filtering effect.

Acknowledgments. We are grateful to D. C. Fritts, T. Nakamura, and M. K. Ejiri for their helpful comments and suggestions. Y. Katoh and M. Satoh are gratefully acknowledged for their skillful support in the airglow measurements. The airglow images used in this study were obtained in cooperation with IPS Radio and Space Services, Sydney, Australia. This work was supported by a Grant-in-Aid for Scientific Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan (13573006, 11440145, and 13136201).

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