Gravity wave activity observed by airglow imaging from different sites in Brazil

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Abstract

An all-sky CCD imager for the airglow OH, O_2 and OI (557.7 nm) emissions was operated at Cachoeira Paulista (CP), Brazil (23^0 S, 45^0 W), under collaboration with Utah State University, USA, in a period of 1998-2000. Another all-sky imager, which belongs to Instituto Nacional de Pesquisas Espaciais, has been operated at São João do Cariri (Cariri), Brazil (7^0 S, 36^0 W) since October 2000. Dominant gravity wave components were investigated by using the image data from the two sites. Wave characteristics observed at CP (October 1998 to September 1999) shows horizontal wavelength of 5 to 60 km, period of 5-35 minutes and horizontal phase velocity of 1-80 m/s. Band-type waves (horizontal wavelength between 10 and 85 km) showed a clear seasonal dependency in the horizontal propagation direction, propagating to southeast in summer and to northwest in winter. The Cariri data (September 2000 to August 2001) showed horizontal wavelength of 5 to 65 km, with the period of 5-55 minutes and horizontal phase velocity of 5-105 m/s, much higher than CP. Band-type waves also exhibited a seasonal dependency in the horizontal propagation direction, propagating to southeast in summer and northeast in winter.

Introduction

Airglow imaging technique provides simple and useful method to investigate horizontal characteristics of the atmospheric gravity waves and their temporal evolution in the upper mesosphere and lower thermosphere (MLT) region. Most of the airglow image measurements reported in the literature concern to short-period (<1 hour) wave characteristics, which falls into two distinct categories, one called “bands” and the other named “ripples”. The bands are horizontaly extended, long-lasting wave patterns and exhibit horizontal wavelengths of several tens of kilometers and horizontal phase velocities up to 100 m/s (e.g. Clairemidi et al., 1985). These patterns have been attributed to freely propagating or ducted short-period gravity waves (Walterscheid et al., 1999, Isler et al., 1997; Taylor et al., 1987). Ripples are short-lived (<45 min) small-scale waves with restricted spatial extent patterns (Peterson, 1979), and are thought to be generated in-situ by localized shear or convective-type instabilities in a total wind field (Taylor and Hapgood, 1990; Hecht et al., 1995).

Nakamura et al., (1999) analyzed 18 months of OH image data and extracted dominant gravity wave components. They found a seasonal variation of the wave characteristics. For the waves with horizontal wavelength longer than 18 km, the propagation direction was eastward in summer and westward in winter. Walterscheid et al. (1999), from 9 months of airglow image observations, concluded that many waves were thermally ducted. For the waves with the horizontal wavelength of a few tens of kilometers preferential propagation direction was poleward in summer and equatorward in winter. Hecht et al., (2001) suggested that most of the waves observed during the summer solstice originated from the south or southeast of the observation site. Medeiros et al. (2003) found from the Cachoeira Paulista image data that propagation direction of the bands showed a seasonal variation. In summer the preferential propagation direction is towards southeast. In winter the preferential propagation direction is towards northwest. The present work reports new image measurements of the short period waves observed at two different latitudes in Brazil, one at Sao Joao do Cariri (7^0 S, 36^0 W) and the other at Cachoeira Paulista (22.7^0 S, 45.0^0 W) in Brazil. The Figure 1 shows the two locations.

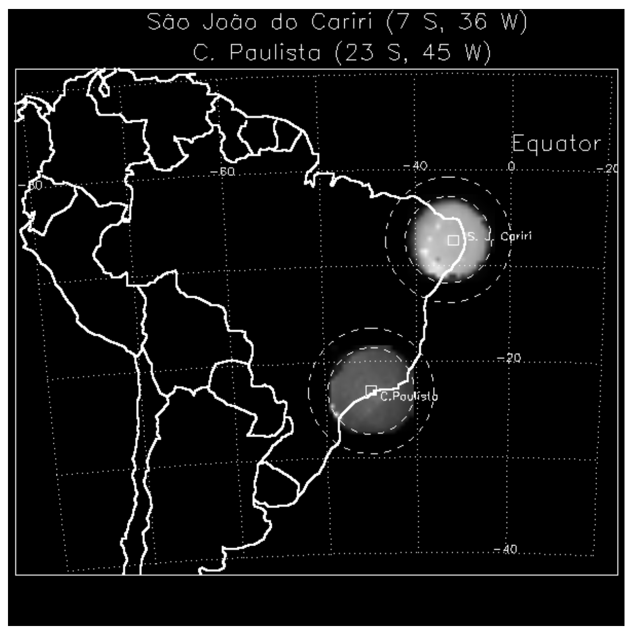

Fig. 1 – Two airglow observation sites of the present work, one at Cariri (7S°, 36°)

Instrumentation and methodology

The airglow observations have been carried out at Cachoeira Paulista, (23^0 S, 45^0 W), using an all-sky imaging system. This is a collaborative program between the Instituto Nacional de Pesquisas Espaciais (INPE), Brazil and the Space Dynamics Laboratory, Utah State University (Dr. M. J. Taylor). The CCD imager consists of a large area (6.45 cm^2), high resolution, and 1024x1024 back-illuminated array with a pixel size of 14 bits. The

high quantum efficiency (~80% at visible wavelengths), low dark current (0.5 electrons/pixel/s), low readout noise (15 electrons rms), and high linearity (0.05%) of this device made it possible to achieve quantitative measurement of the airglow emissions. The camera uses a fast (f/4) all-sky telecentric lens system that enables high signal-to-noise (20:1) ratio images of wave structure to be obtained with time integration of typically 15 s for the near-infrared OH emission (715-930 nm pass-band) and 90 s for the OI (557.7 nm), O_2, and OI(630.0 nm) emissions. The image was binned on-chip down to 512x512 resolution to enhance the signal-to-noise ratio.
The airglow observation was also carried out at São João do Cariri. (7°S, 35° W), by an all-sky imaging system, under collaboration with the Instituto Nacional de Pesquisas Espaciais (INPE). A fish-eye 180° wide-angle lens followed by a telecentric lens system with an interference filter produces a narrow band monochromatic image on the CCD camera. A large area (6.45 cm 2) CCD camera, with 1024 x 1024 pixels, thermoelectrically cooled to -36° C, was used in the present observations. The all-sky imager covers a zenith angle range of about ~85 degrees, not 90 degrees owing to the local sky viewing conditions. That corresponds to a horizontal distance of about 1000 km diameter at the height of 87 km where the OH emission layer is assumed to be. Figure 2 shows a 512x512 resolution all-sky CCD raw image showing a gravity wave event in the OH airglow emission detected in CP and Cariri.

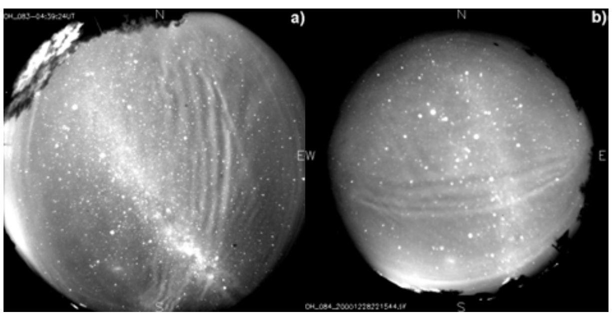

Fig. 2 - a) Airglow all-sky image, with 512x512 resolution, showing a gravity wave event in the OH emission observed at Cachoeira Paulista on the night of January 19, 1999, 01:39 UT, b) the same but at Cariri on the night of December 28, 2000, 01:15 UT.

After processing the all-sky images, it is now possible to determine the horizontal wave parameters, horizontal wavelength, period and phase velocity, by using a standard 2-D FFT analysis. The advantage of this method is that it is possible to process all of the monochromatic waves present in the image individually. We can identify the gravity wave content in any part of the image by isolating a region of interest, taking the 2-D FFT of it and identifying peaks in the frequency spectrum (Medeiros et al., 2003). The horizontal wavelength of the wave can be determined by computing the inverse of the distance of the peak from the origin. The wave period (and hence the phase speed) can be determine taking one-dimensional FFT in the time of complex 2-D FFT in space. The peaks in the 1-D FFT correspond to the wave frequencies. Another way to show these events is to exhibit them in three dimensions.

Results
The airglow all sky measurements at CP were carried out from October 1998 to September 1999. Despite the restrictions imposed by tropospheric clouds, approximately 433 hours of useful data were recorded from the 69 nights, in which 283 wave events were identified. The mean rate of occurrence of the events was 0.7 events/hour with a higher rate in summer and winter than the equinoxes. At Cariri the observations were carried out from September 2000 to August 2001. There was no observation in March due to a technical problem. In spite of the frequent tropospheric cloud covering, approximately 660 hours of useful data were acquired from the 132 nights. The mean rate of occurrence of the events was 0.8 events/hour. Similar to CP, the frequency of occurrence of the event in Cariri is high in summer and winter and low in the equinoctial months.
Figure 3 shows the frequency of occurrence of the wave event as a function of horizontal wavelength at CP and Cariri. The data were binned into histograms of 5 km width. The frequency of occurrence at CP exhibits somewhat a broader range of the horizontal wavelength extending from ~10 to 60 km, and 85% of the observed bands had wavelength less than 15 km. The mean wavelength was 22.9 km. The frequency of occurrence at Cariri shows a wide range of horizontal wavelength extending from10 to 85 km and a majority of the bands had wavelength between 15 and 30 km.

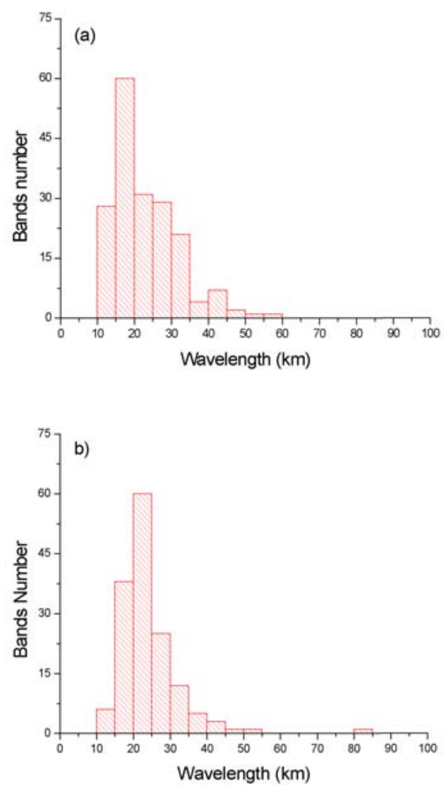

Fig. 3 – Frequency of occurrence of the gravity waves with the horizontal wavelength from 5 to 100 km with 5 km of interval at Cachoeira Paulista (CP) (a) and Cariri (b).

Histogram of the frequency of occurrence against the wave periods (binned with 2 minutes intervals) is shown in Figure 4 for CP and Cariri.

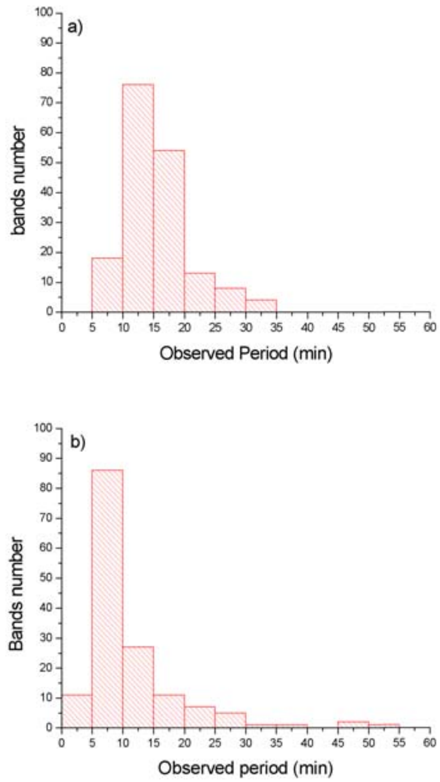

Fig. 4 – Frequency of occurrence of the wave period, with 5 min interval for CP(a) and Cariri (b).

It can be seen a clear difference between the CP and Cariri data. The histogram of CP (Figure 4a) shows somewhat wide range of period, 97% of bands exhibiting periods less than 8 minutes, with an averaged wave period of 15.6 min. Most of the waves fall into a range of 10 to 20 minutes. On the other hand the histogram of Cariri (Figure 4b) shows a narrow range of distribution between 5 and 15 minutes. The highest frequency of occurrence happens in a 5 to 10 minutes range. A difference in the wave characteristics between CP and Cariri becomes much clear when we look into the histogram of phase speed distribution.

Figure 5 shows the distribution of phase speed plotted with 10 m/s intervals for CP and Cariri. The phase speed at CP concentrates in a range of 10 to 40 m/s, with an average of 26.1 m/s. At Cariri, on the other hand, the phase speed has a distribution that extends from 5 to 105 m/s with a higher occurrence between 35 and 60 m/s. The mean phase speed was 37 m/s. Clearly, the phase speed observed at Cariri is higher than at CP.

The wave propagation directions are summarized in Figure 6. The frequency of occurrence diagram is binned in a 15° interval. The distribution of the CP data is highly anisotropic, exhibiting two directions of preference:

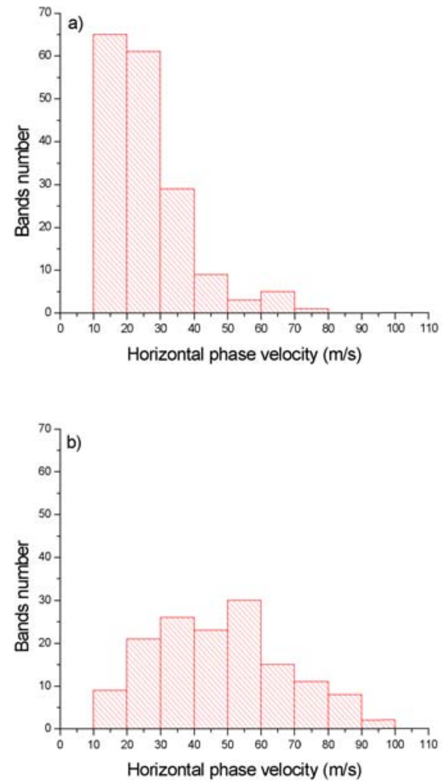

Fig. 5 – Frequency of occurrence of the horizontal phase velocity, with 10 m/s interval for CP (a) and Cariri (b).

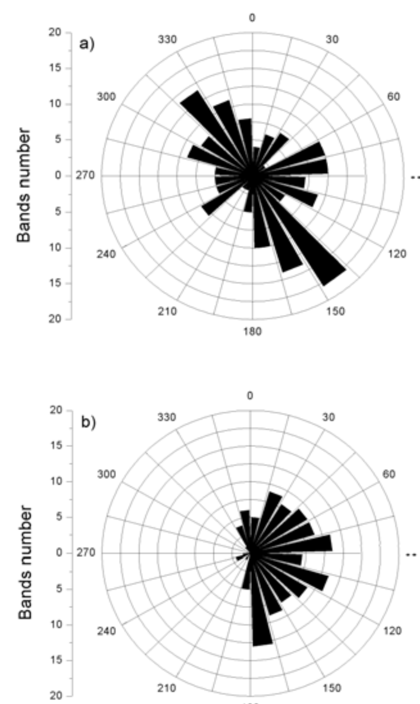

Fig. 6 – Frequency of occurrence of the propagation direction of the gravity waves (band type) observed at CP (a) and Cariri (b).

southeast (azimuth range 90°-180°) and northwest (azimuth range 270°-360°). Contrasting to it, the Cariri data (Figure 6b) show preferential wave propagation direction to east (from continent to sea). From a total of 150 bands observed, the 131 events (87,3%) showed a propagation direction towards the east direction.

In order to examine seasonal tendency of the wave parameters, the data were grouped in four seasons: summer (November, December, January and February), autumn (March and April), winter (May, June, July and August) and spring (September and October). No clear seasonal variation was found against the wavelengths, periods and phase velocities from both the observation sites. However, the propagation direction did show a clear seasonal dependency. Figure 7 shows histograms of the propagation direction of the CP data, dividing them into 4 seasons. During the summer the preferential propagation direction is southeast. In winter it changed towards northwest. In the other seasons no clear preferential propagation direction was observed. In the case of Cariri, shown in Figure 8, the preferential propagation direction is towards southeast during the summer and towards northeast during the winter.

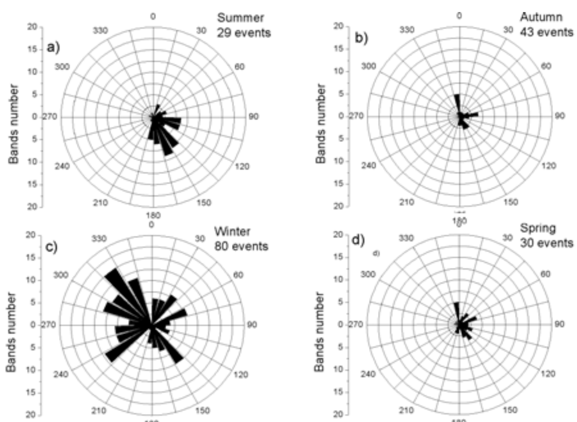

Fig. 7 – Propagation direction distribution of the gravity waves (band types) at Cachoeira Paulista (CP): a) summer, b) autumn, c) winter and d) spring.

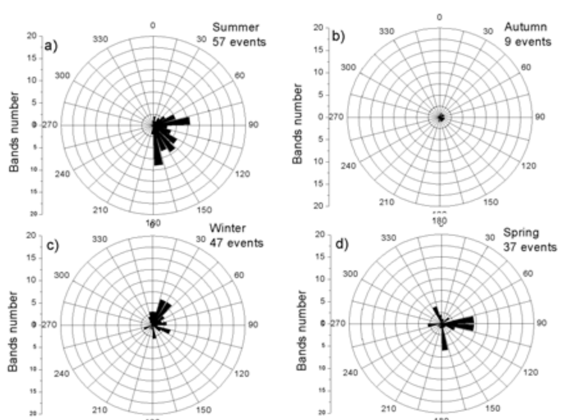

Fig. 8 – Same as Fig. 7 except for Cariri.

Discursion

The band type gravity waves in the mesopause region observed by OH airglow imager from two different latitude regions, one from the equator (Cariri, 7S^0) and the other from the low-middle latitude (Cachoeira Paulista (CP, 23^0 S) showed a different feature in their wave characteristics. The waves observed at Cariri have a narrow range of horizontal wavelength (15-30 km), short period (5 – 10 minutes), close to the Brunt Vaisala period. The phase velocity of the Cariri data has a wide range from 10 to 90 m/s. These characteristics are different as compared to those of CP as mentioned in the previous section. The anisotropy of the wave propagation direction also shows some different feature in the two sites.

The wave propagation direction in the mesopause region depends on two factors, its source location in the lower atmosphere against the observer and background wind field below the observation layer. Gravity waves propagating upward from the lower atmosphere are absorbed into the mean flow as they approach to a critical layer where the intrinsic frequency of the wave is Doppler shifted to zero. This situation may occur at any height when the local horizontal wind speed along the direction of propagation equals to the observed horizontal phase speed of the gravity wave. Gravity waves with horizontal phase velocities outside of this region would not meet by chance a critical layer and should be observable. This fact suggests that wave filtering by wind can play an important role in the seasonal variation of the waves over CP and Cariri. Taylor et al., (1993) and Medeiros et al. (2003) reported the effect of wind filtering of the gravity waves. The anisotropy of the wave propagation direction observed mainly in summer and winter in the both sites could be due to seasonal variation of the stratospheric and mesospheric wind fields.

The observed anisotropy also could be due to a non-uniform distribution of the gravity wave sources. If it is partly true, as seen in the Figures 7 and 8, the wave sources should be located mainly at the northwest of the observer in summer and at southeast in winter in case of CP, and at northwest of the observer in summer and at southwest in winter for Cariri. Several workers have studied gravity wave seeding mechanism. Thunderstorm activity has been identified as a possible source of short-period gravity waves (Taylor and Hapgood (1988), Walterscheid et al.(1999) and Hecht et al. (2001)).The sources function and upward propagation mechanism for the data presented in the present work are under investigation.

Further measurements are needed before any conclusion can be drawn. It should be emphasized that in our present results, the observed phase velocities at Cariri are higher than those at CP. Nakamura et al. (2002) also found a higher phase velocity at Jacarta (6.9°S, 107.9°E) and suggested that it could be due to weak wind velocity at equatorial region. In order to check it vertical wind profiles for 23^0 S and 7^0 S from a wind model HWM93 (Hedin, 1996) are plotted in Figure 9. It can be seen that the wind velocities from the stratosphere to mesosphere are always higher, 10 to 30 m/s, at 23^0 S than 7^0 S. However, it is too early to conclude that the difference in the observed phase speed is mainly due to the Doppler effect.

Conclusions

Observations of the band type gravity waves by airglow imaging technique were carried out at Cachoeira Paulista

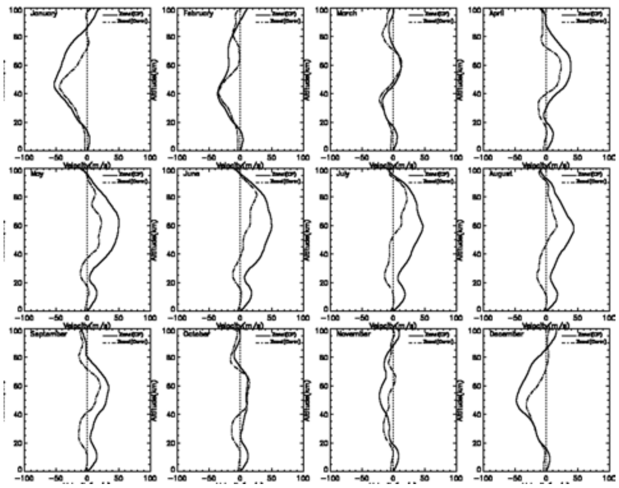
Fig. 9 – Zonal winds from January to December for 23 S at CP (solid line) and for 7 S at Cariri (broken line) from the HWM93 model.

(23° S, 45° W) and São João do Cariri (7° S, 36° W) in Brazil. The directions of wave propagation are significantly anisotropic in the two sites, southeast during summer and northwest during the winter at CP and southeast in summer and northeast in winter at Cariri. These results indicate that the anisotropy was mainly due to wave filtering process by the stratospheric and mesospheric winds in agreement with Taylor et al. (1993) and Medeiros et al. (2003) conclusions. Larger horizontal phase speed observed at Cariri could be due to weaker zonal wind in the equatorial region compared to the middle latitude wind field.

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References

Hecht J. H., Walterscheid R. L., Hickey M. P., and Franke S. J., Climatology and modeling of quasi-monochromatic atmospheric gravity waves observed over Urbana Illinois, *J. Geophys. Res., 106*, 5181-5191, 2001.

Hecht J. H., Howat S. K. R., et al., Observations of spectra of intensity fluctuations of the OH Meinel nightglow during ALOHA-93. *Geophy. Res. Lett.,* 22(20) 2873-2876, 1995.

Hedin A. E., E. L. Fleming, A. H. Manson, F. J. Schmidlin, S. K. Avery, R. R. Clarck, S. J. Franke, G. J. Fraser, T. Tsuda, F. Vial and R. A. Vincent, Empirical wind model for the upper, middle and lower atmosphere, *J. Atmos. Terr. Phys***.**, 58, 1421,1996.

Isler J. R., Taylor M. J., and Fritts D. J., Observational evidence of wave ducting and evanescence in the mesosphere, J*. Geophys. Res., 102*, 26301-26313, 1997.

Medeiros, A. F.; Taylor, M. J.; Takahashi, H.; Batista, P. P.; Gobi, D., An Investigation of gravity wave activity in the low-latitude upper mesosphere: propagation direction and wind filtering, *Journal of Geophysical Research*, accepted, 2003

Nakamura, T.; Aono, T.; Tsuda, T.; Martimingrum, D. R. and Achmad, E. Mesospheric gravity waves over tropical convective region observed by OH airglow imaging in Indonesia, THIRD PSMOS INTERNATIONAL SYMPOSIUM ON DYNAMICS AND CHEMISTRY OF THE MLT REGION, Foz do Iguaçu Planetary Scale Mesopause Observing System, 2002

Nakamura T., Higashikawa A., Tsuda T., and Matsushita Y., Seasonal variations of gravity wave structures in OH airglow with a CCD imager at Shigaraki, *Earth Planets Space, 51*, 897-906, 1999.

Peterson A. W., Airglow events visible to the naked eye, *Appl. Optics*, 22, 3390-3393, 1979.

Taylor M. J. and M. A. Hapgood, On the origin of ripple-type wave structure in the nightglow emission, *Planet. Space Sci***.**, 38, 1421-1430, 1990.

Taylor M. J., and Hapgood M. A., Identification of a thunderstorm as a source of short period gravity waves in the upper atmospheric nightglow emission, *Planet. Space Sci., 36*, 975-985, 1988.

Taylor M. J., Hapgood M. A., and Rothwell P., Observations of gravity wave propagation in the OI (557.7 nm), Na (589.2 nm) and the near infrared OH nightglow emissions, *Planet. Space Sci, 35*, 413-427, 1987.

Taylor M. J., Ryan E. H., Tuan T. F., and Edwards R., Evidence of preferential directions for gravity wave propagation due to wind filtering in the middle atmosphere, *J. Geophys. Res.***,** *98(A4)*, 6047-6057, 1993.

Walterscheid R. L., Hecht J. H., Vicent R. A., Reid I. M., Woithe J., and Hickey M. P., Analysis and interpretation of airglow and radar observations of quasi-monochromatic gravity waves in the upper mE), *J* esosphere and lower thermosphere over Adelaide, Australia (35° S, 138°). *Atmos. Sol. Terr. Phys., 61*, 461-468, 1999.