Study of the gravity wave propagation direction observed by airglow imaging in the South American sector

Amauri F. Medeiros (Universidade Federal de Campina Grande), Hisao Takahashi (Instituto Nacional de Pesquisas Espaciais), Ricardo A. Buriti (Universidade Federal de Campina Grande), Kiosthenes. M. Pinheiro (Universidade Federal de Campina Grande) and Delano Gobbi (Instituto Nacional de Pesquisas Espaciais)

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Abstract

Airglow all sky imaging observation has been carried out in three different locations in the south America, at Cachoeira Paulista (22.7 S, 45.0 W) in 1999, São João do Cariri (7.5 S, 36.5 W) in 2001 and Boa Vista (2.8 N, 60.7 W) in 2002. Comparing the atmospheric gravity wave characteristics retrieved from the image data for the three different sites and including a previous work at Alcantara (2.3 S, 44.5 W) carried out by Taylor et al. (1997), we found that there is a preferential propagation direction, from the Continent to Atlantic Ocean. Possible source of the wave generation is discussed.

1. Introduction

Short-period gravity waves with its wavelength from a few kilometers to a few hundred of kilometers have been studied by using sensitive cooled-CCD imagers measuring upper mesosphere airglow emissions (e.g., Taylor et al., 1995a; Nakamura et al., 2001; Swenson and Liu, 1998; Yamada et al., 2001; Ejiri et al., 2001,2002; Smith et al., 2003; Shiokawa et al., 2003; Liu and Swenson, 2003). The airglow imaging technique provides a simple and useful method to investigate horizontal characteristics of 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 short-period (<1 hour) wave characteristics. These waves have been attributed to freely propagating or ducted short-period gravity waves (Walterscheid *et al.*, 1999, Isler *et al.*, 1997; Taylor *et al.*, 1987).

Nakamura *et al.*, (1999) analyzed 18 months of OH image data obtained at Shigaraki (35° N, 136° E), and extracted 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 in Adelaide (35° S, 138° E), concluded that many waves were thermally ducted. For the waves with horizontal wavelengths of a few tens of kilometers, the 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. The data were obtained at Urbana (40° N, 88°W). Medeiros *et al.* (2003) found that the propagation direction of the bands observed at Cachoeira Paulista(22.7° S, 45.0° W) showed a seasonal variation. In summer, the preferential propagation direction was towards southeast. In winter, it was towards the northwest.Taylor et al. (1997) carried out first airglow image observation at Alcantra (2.3° S, 44.5° W) in South America. After this work Medeiros et al. (2003, 2004a) studied mesospheric gravity wave climatology from the airglow image data at Cachoeira Paulista (23° S, 45° W) and São João do Cariri (7° S, 36° W). In addition to these data, recently we got another data set during the COPEX (Conjugate Point Equatorial Experiment) Campaign at Boa Vista (2.8° S, 60.7° W) in 2002. The purpose of the present work is, therefore, to compare these image data from 4 different observation sites and to investigate gravity wave characteristics between them, focusing a subject mainly in the wave propagation direction.

2. Instrumentation

The airglow observation was carried out at Cachoeira Paulista, using an all-sky imager. It was 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 of 14 bits. The high quantum efficiency, low dark noise level (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 monocromatic images of wave structure to be obtained with a 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 (864.5 nm), and OI(630.0 nm) emissions. The image was binned on-chip down to 512x512 resolution to enhance the signal-to-noise ratio. Another airglow imager operated at Cariri has a similar optical system and filter characteristics to that was operated at Cachoeira Paulista.

After processing the all-sky images, from a warped image to un-warped one with geographic coordinates, the gravity wave parameters, horizontal wavelength, period, phase velocity and propagation direction are retrieved by using a standard 2-D FFT analysis. The horizontal wavelength can be determined by computing inverse of the distance of the peak from the origin. The wave period (and hence the phase speed) can be determined by taking one-dimensional FFT of the complex FFT in time space (Garcia and Taylor, 1997). The peaks in the 1-D FFT correspond to the wave frequencies. Detail of the data analysis has been published elsewhere (Medeiros et al. (2003).

In the present work, The OH, O2b and OI5577 images were used to calculate the wave characterisitcs. These mesospheric emission layers are located at around 87 to 97 km of altitude (Baker and Stair, 1988). Therefore the imager view field is around 1000 km of diameter on that height (~ 90 km). In the present work we classified as a wave event if any one of the emission layers (OI5577, O2b and OH) show wavelike structure in their image.

3. Observations

Airglow all-sky imaging observations were carried out at Cachoeira Paulista (CP) under collaboration between Instituto Nacional de Pesquisas Espaciais (INPE), Brazil and Space Dynamics Laboratory, Utah State University in the period from October 1998 to August 2000. An airglow observatory near the equator at São João do Cariri (Cariri) was inaugurated in September 2000. The observation site was chosen because of a good weather condition (dry and less cloud formation) and also a low level of city light contamination. The same imager was dislocated to Boa Vista (BV) during the Conjugate Point Equatorial Experiment (COPEX) Campaign conducted by INPE in September-December 2002.

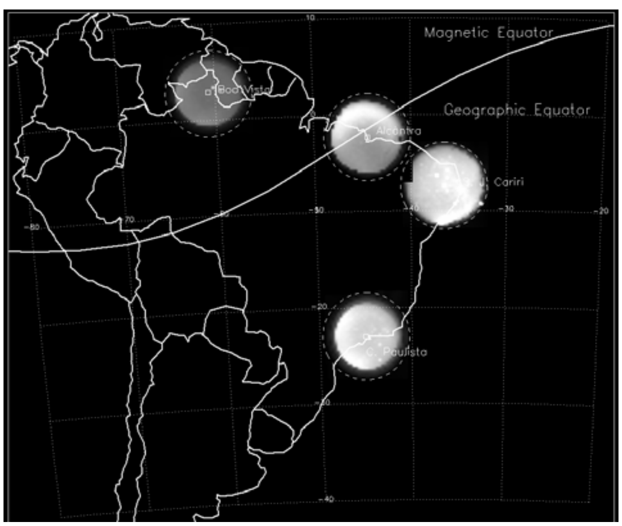

Fig. 1 - Airglow all-sky image observation sites at Boa Vista, Alcantara, Cariri and Cachoeira Paulsta. The white circles indicate diameter of the image area of observation.

As can be seen in Figure 1, the 2 sites (Cariri and Cachoeira Paulista) are near the coast, and Boa Vista is located to the north of Amazon forest. Observation sites, their geographic coordinates and observation period used in the present analysis are presented in Table 1. As mentioned before the observation periods of the four observation sited are different, different year and season. In order to compare between them in the present work, therefore, we chose the data with a same season, from October to December, but keeping in mind of that they are from the different years. The image data at Alcantara (AL) was obtained by M. J. Taylor during GUARA Campaign (Taylor et al., 2001). In the present study we also referred them although the data were obtained in 1994.

Table 1 – Airglow all-sky image observation sites, geographic coordinates and observation period used in this work

Site	**Geographic Coordinates**	**Observation Period**
Alcântara (AL)	(2.3 S, 44.5 W)	August-October, 1994
Cachoeira Paulista (CP)	(23 S, 45 W)	October-December, 1999
São João do Cariri (Cariri)	(7 S, 36 W)	October-December, 2000
Boa Vista (BV)	(2.8 N, 60 W)	October-December, 2002

4. Results

In order to compare the gravity wave characteristics between the 4 different locations, we chose band type waves. It is believed that the band type waves have a phase propagating mode with a long distance (longer than a few hundreds of km) and transport momentum. They are different to the ripple type which could be generated locally by wind shearing and/or wave to wave interaction (Taylor et al., 1990).

Horizontal wavelength and phase velocity: Three sites, Boa Vista, Cariri and Cachoeira Paulista, show similar feature on the horizontal wavelength, varying from 15 to 35 km with an average of around 25 ± 2 km. Taylor et al. (1997) also observed similar characteristics in the wavelength at Alcantara. Concerning the horizontal phase velocity, on the other hand, we found that there is a clear difference between the sites. The Cachoeira Paulista data showed the velocity varying from 10 to 45 m/s with a peak at around 20-30 m/s. On the other hand the Boa Vista and Cariri data present rather wide range of velocity varying from 10 to 90 m/s, much faster than that of Cachoeira Paulista. Taylor et al. (1997) presented a similar result from Alcantara, the velocity varying from 20 to 75 m/s. Faster propagation velocity in the equatorial region compared to the low to middle latitudes has been reported by Nakamura et al. (2002) and Medeiros et al. (2004). They pointed out that the difference could be due to the background wind velocity, which is less in the equatorial region compared to the middle latitude. Filtering effect of the waves and Doppler effect for the phase velocity should be less in the equatorial region.

Propagation Direction: The wave propagation directions are summarized in Figure 2. The frequency of occurrence is binned in 15° intervals.

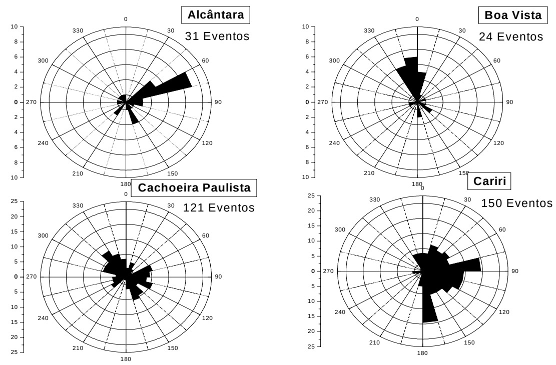

Fig. 2 – Gravity wave propagation direction diagram observed at Boa Vista, Cariri, Cachoeira Paulista and Alcantara. The radius indicates a number of events grouped in each 15 °.

At Boa Vista the preferential direction of propagation is toward north. From the 24 events, about 70% of the cases showed a component moving from south to north. It is interesting to note that in the south of Boa Vista a huge Amazon Forest is extended. The Cariri data showed a preferential wave propagation direction to the east, again from the continent to the Atlantic Ocean. From a total of 150 bands observed, the 131 events (equivalent to about 87 %) showed a propagation direction towards the east. From the Table 1 of Taylor et al. (1997) we plot a diagram for Alcantara in Figure 2. As they reported the preferential direction of propagation was toward northeast (the azimuth range between 45 and 75 degrees). Since the coast at Alcantara is extended from northwest to southeast, the direction of propagation is again from the continent to seaside. The propagation direction at Cachoeira Paulista is somewhat different compared to the equatorial region, showing the direction to the east and/or southeast. If we plot these results on a map it is not difficult to conclude that the observed waves mainly have their propagation direction from the continent to the Atlantic Ocean side.

5. Discussion

The different propagation directions of the mesospheric gravity wave observed at four different observation sites in the South America Continent should be worthwhile to investigate. The wave propagation direction in the mesopause region depends on two factors, its source location in the lower atmosphere, relative to the observer, and the background wind field in the stratosphere and mesosphere. Gravity waves propagating upward from the lower atmosphere are absorbed into the mean flow as they approach 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 apparent 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. In order to check the background wind filtering effect we plot, in Figure 3, stratosphere-mesosphere wind blocking diagram for the October–December season using the HWM93 wind model (Hedin et al., 1996). The westward blocking wind occurres mainly in November to December, and it is faster at Cachoeira Paulista (~50 m/s) than at Cariri (~30 m/s). In the figure the observed wave propagation directions are also plotted for comparison. The length of the each arrow now indicates velocity of the wave propagation. For the Cariri, Boa Vista and Alcantara data, the observed phase velocities are much faster than the blocking wind velocity. According to the statistics, a major part of the waves have its phase velocity faster than 30 m/s (Medeiros et al. 2004). Therefore, the absence of waves towards west should indicate that there is little wave source in the east of the observer. For the Cachoeira Paulista data, the blocking wind seems to be significant. The strong westward wind could filter the waves propagating westward. The effect of filtering for the Cachoeira Paulista data, therefore, can not be ruled out.

Focusing the discussion into gravity wave source, from the propagation directions of the four observation sites one can suppose that the gravity waves should have a same wave generation source in the continent. One of the strong candidate of the wave generation mechanism is tropospheric convection as having been suggested by several workers (Taylor et al., 1988, Medeiros et al., 2004a). Occurrence of the convection activity in the tropical region of the South America can be presented by its lightning activity. In Figure 4, optical observation of the lightning over South America during October-December 2002 are plotted (http://thunder.nsstc.nasa.gov/lightning-cgi-bin/lis/LISSearch.pl). Densed lightning activities can be seen in the central part of the continent, extending from the near equator to 30ºS. The highest activity zone is the southern part of Brazil, below 25 S. Very few amount of activity can be seen over Atlantic Ocean during this period. If one compares it with Figure 3, it seems to be clear that the gravity waves observed at the 4 locations have a common source, tropospheric convection activity.

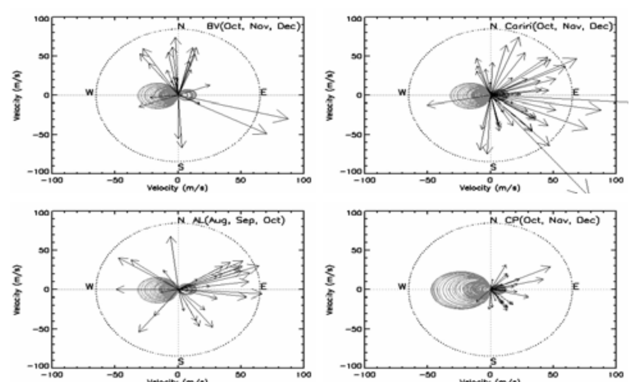

Fig 3 - stratosphere-mesosphere wind blocking diagram for the October–December season using the HWM93 wind model (Hedin et al., 1996) together with the observed wave propagation directions.

6. Conclusions

Mesospheric airglow all-sky image observations were carried out at four different sites in South America Continent near the equator and low latitudes. The observed wave (band type) propagation directions reveal that a major part of the waves have their direction from Continent toward coast. At Boa Vista, the direction is northward, Alcantara towards northeast, Cariri towards eastward, and at Cachoeira Paulista it is towards east. These results suggest that during the period of October to December, the gravity wave source for the observers are in the Continent, most probably, generated by tropospheric cloud convection activities.

Acknowledgments

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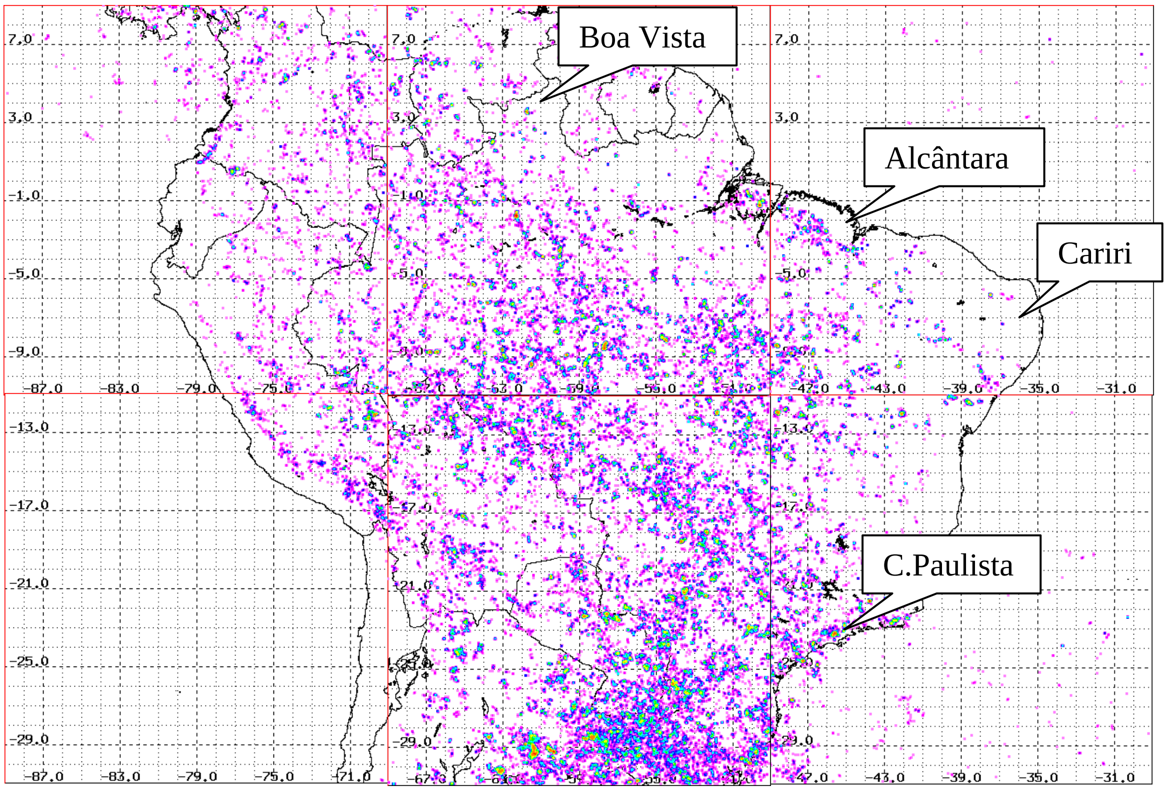

Fig. 4 - optical observation of the lightning over South America during October-December 2002