GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L08807, doi:10.1029/2008GL036936, 2009

Evidence of mesospheric gravity-waves generated by orographic forcing in the troposphere

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Received 8 December 2008; revised 23 February 2009; accepted 3 March 2009; published 17 April 2009.

[1] We report on the first imaging observations of stationary mesospheric gravity-waves in the three nightglow emissions of OH (695–1050 nm), Na (589.3 nm) and O(^{1}S) (557.7 nm). The waves were observed in all-sky images at the El Leoncito Observatory (ELO), Argentina (31.8°S, 69.3°W), during the period of 1–8 July 2008. Over the course of each night, the band-like wave features exhibited a zero or near-zero observed horizontal phase speed and had lifetimes of several hours. These factors, coupled with the winds measured locally, and the orientation of the waves to the Andes mountain range located nearby, suggested that the waves were mountain waves generated by ~70 ms^{-1} eastward winds flowing over the Andes. **Citation:** Smith, S., J. Baumgardner, and M. Mendillo (2009), Evidence of mesospheric gravity-waves generated by orographic forcing in the troposphere, *Geophys. Res. Lett.*, *36*, L08807, doi:10.1029/2008GL036936.

1. Introduction

[2] A large body of theoretical and observational work exists on the subject of the orographic generation of gravity waves in the earth's atmosphere. These waves, known as mountain waves, have been observed in the troposphere [e.g., *Scorer*, 1949; *Beer*, 1974] and the stratosphere [e.g., *Eckermann and Preusse*, 1999; *Preusse et al.*, 2002; *Jiang et al.*, 2002], via several techniques such as photometers, radars, and satellites. Here we present imaging observations showing unambiguous evidence for mountain waves in three night-time airglow emissions in the upper mesosphere.

2. Instrumentation and Data Reduction

[3] The Boston University airglow imaging system at the El Leoncito Observatory (ELO) [*Smith et al.*, 2006; *Martinis et al.*, 2006] is equipped with a 16mm fish-eye lens which records an all-sky view of the night-time sky using a high-efficiency 2048 × 2048-pixel back-illuminated CCD detector. Several night-time emissions are recorded nightly using narrow-band (1.2–1.8 nm) filters (except for the OH filter): OH (broadband IR, 695–1050 nm), Na (589.3 nm) and O(^{1}S) (557.7 nm) from the upper-mesosphere (80–100 km), and O^{1}D (630.0 nm) and O(^{5}P) (777.4 nm) from the thermosphere (~250–400 km). The location of El Leoncito is shown in Figure 1.

[4] Nightly observations are made during clear, moonless periods, with each filter being cycled sequentially. The observing schedule, such as integration times and filters, can be changed very easily to suit the observing requirements. For the observations reported on here, the integration times were all 120s, except for 30s for the OH filter, and so each filter was cycled every 5–6 minutes.

[5] The raw all-sky images were reduced using our standard procedure; initial bias- and dark-subtraction, then flat-fielding to remove effects of vignetting due to the imaging system and van Rhijn brightening. A routine was then used to remove stars and the Milky-Way from the images and then calibrated photometrically into Rayleigh brightness units. Finally, the images were mapped onto the Earth's surface using the nominal heights of the layers, a process called unwarping. The assumed heights used for the Na and O(^{1}S) emissions were 90 and 96 km, respectively. During each of the eight nights, measurements of the OH volume emission height profile were available from the SABER instrument aboard the NASA TIMED satellite during overpasses of the ELO site http://saber.gats-inc.com). The overpass times tended to occur during the middle of the observation periods between 03:30 UT and 05:00 UT. Consequently, a measured mean height of 85 km (σ = 2 km) for the nights was used to unwarp the OH images.

3. Observations and Data Analysis

[6] During the eight nights of 1–8 July 2008, a large and extensive series of small-scale stationary waves were observed to occur in the three mesospheric night-time OH, Na, and O(^{1}S) emissions. The waves were visible particularly in the OH and Na emissions, oriented along the north-south direction and extending almost across the entire sky. They were also present in the O(^{1}S) images during some of the nights, indicating that the waves had penetrated to 96 km in altitude, but these structures were generally too faint to yield useful wave parameters.

[7] Figures 2a–2f show the typical behavior of the wave structures in the OH emission during a single night, in this case 4 July 2008. During the course of each night, and as shown here, the position of the leading wave-front dithered backwards and forwards slightly in position. On a couple of nights, the waves would disappear and reappear in a slightly different position in the sky, but with a similar orientation and behavior. The amplitude of the waves in the 589.3 nm emission was 10–40 R (5–30%) above the background emission and 10–15 R (4–15%) in the 557.7 nm. The largest amplitudes were associated with the most westward of the waves. The background airglow brightness in all three emissions was enhanced by 10–20% due to the stationary wave patterns. Unlike typical band-type gravity

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0094-8276/09/2008GL036936$05.00

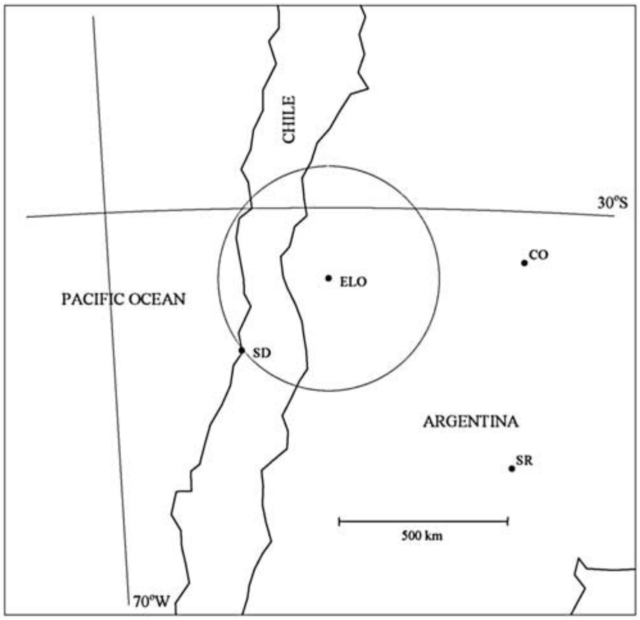

Figure 1. Map showing the location of the El Leoncito Observatory (ELO) in Argentina on the east side of the Andes mountain range. The circle represents 170° of the field of view of the imager shown in the images in Figures 2 and 3. The locations of the radiosonde launch sites of Santa Domingo (SD), Cordoba (CO), and Santa Rosa (SR) (discussed in the text) are also shown.

waves, the waves did not propagate across the sky but exhibited a zero or near-zero horizontal phase velocity with respect to the ground. The waves were also aligned parallel to the Andes mountain range.

[8] Figure 3 shows the nightly time-averaged images of the OH nightglow from the three successive nights of 2–4 July 2008. Remarkably, each unwarped image consists of over $11^1/_2$ hours of ∼60 individual images and shows dramatically the stationary nature of the wave features. The motions of typical gravity-waves and other non-stationary features over the course of the night have been averaged out. The presence of the wave features in the images indicates their temporal stability over the course of each night. Furthermore, the scale-sizes of the stationary waves on consecutive nights were very similar. The mean measured horizontal wavelength of the stationary waves observed during the eight nights was 36.2 km (σ = 2.0 km). The wave structures also showed smaller-scale (∼1–2 km) turbulent structures within the waves themselves.

[9] The large horizontal scale-sizes and lifetimes of the waves indicated that they were not a ripple type instability, a wave phenomenon sometimes observed in all-sky images [e.g., *Taylor and Hapgood*, 1990; *Hecht et al.*, 1997, 2005; *Yamada et al.*, 2001; *Hecht*, 2004]. Ripples are the result of either dynamical or convective instabilities and have wavefronts that are oriented either perpendicular or parallel to the parent wave (depending on the type of instability). They also exhibit small horizontal wavelengths (5–10 km) with lifetimes of 5–15 minutes. In addition, while they are generally advected by the local background wind, they can also exhibit near-zero horizontal phase speeds similar to the behavior observed in the present study. However, ripples tend to be located within a small vertical height region whereas the observed waves were observed simultaneously in the three mesospheric layers centered at 85, 90, and 96 km, respectively, an altitude region spanning 11 km. Furthermore, the orientation and general position of the observed waves were very similar from night to night, i.e., aligned roughly north-south and eastward of the Andes mountain range. In contrast, ripples tend to occur randomly in the sky from night to night and they also occur in more limited regions of the sky.

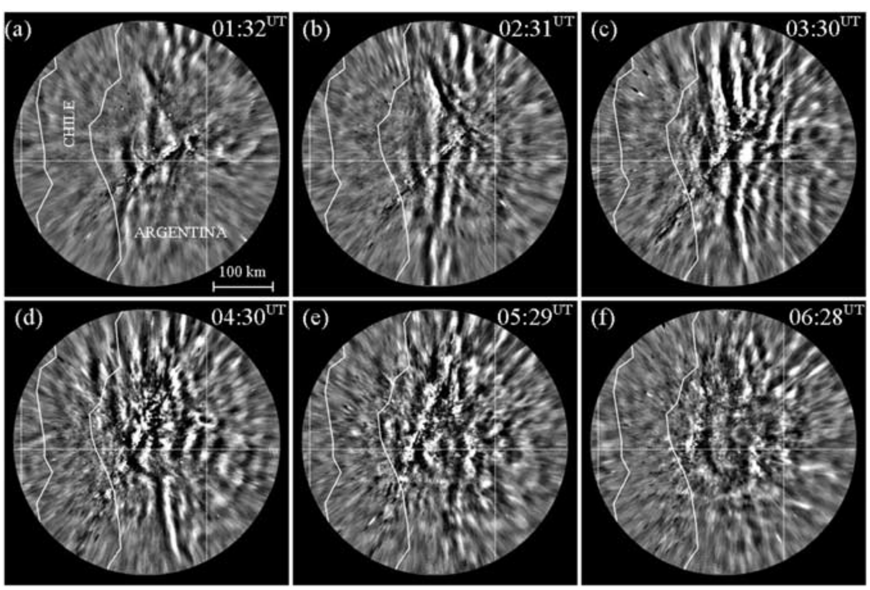

Figure 2. Unwarped 30-second all-sky images showing the behavior of the stationary wave structures in the OH (altitude ∼ 85 km) emission during the night of 4 July 2008. The wave pattern originated just westward of El Leoncito and stretched ∼300 km eastward. The number of waves increased to a maximum at about 03:30UT. The waves dissipated at about 06:30UT. During their lifetime, the wave structures were also composed of turbulent structures with scales of 1–2 km and smaller.

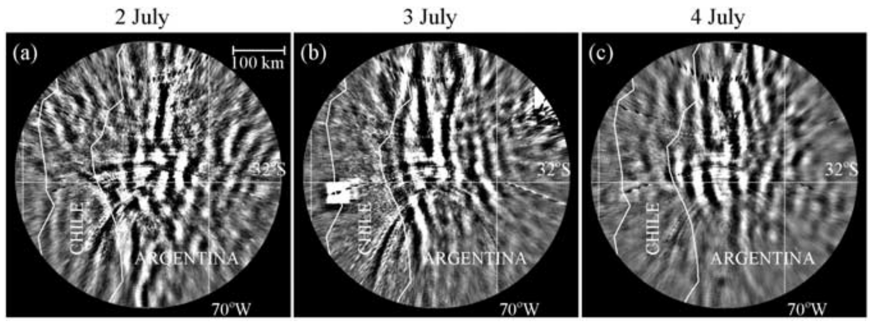

Figure 3. Unwarped all-sky time-averaged OH images, each obtained from averaging ~60 images spanning a time period of over 11.5 hours, on the three successive nights of (a) 2, (b) 3, and (c) 4 July 2008. The field of view of the images is 535 km × 535 km. A large and extensive stationary wave structure oriented North-South and parallel to the Andes range is clearly visible in the OH emission at 85 km altitude. Similar structures were visible in the Na images from near 90 km altitude and also faintly in the O(^{1}S) emission near 96 km altitude (not shown).

[10] Figure 4 shows the time history plots of the three nightglow emissions during the five nights of 1–5 July 2008. The plots were generated by sampling a North-South 300 km-wide strip, aligned along the east-west direction and centered on the ELO, from each individual 30-second unwarped image (such as shown in Figure 2). Each strip was then averaged in latitude into a single 1-dimensional array. Each array was then placed together vertically as a function of time. Hence, time increases along the horizontal axis and the zonal direction is the vertical dimension. The ELO is situated along the middle of the plots at zenith, with the westward direction downwards and eastwards upwards.

[11] The three airglow emissions exhibited phase differences indicating vertical wavelengths of 25 to >100 km. The majority of the wave structures indicated evanescence or an upward propagation of the waves (downward phase progression), but on one of the nights there was evidence of downward wave propagation, i.e., the phase of the waves was directed upwards with altitude.

[12] The motion of typical horizontally propagating gravity-waves in the type of plots shown in Figure 4 would be exhibited as sloping and curved features. For example, one can see the diurnal motion of bright stars that were not removed entirely in the plots as bright and dark "S"-shaped features. In contrast, the stationary waves are clearly evident as a series of horizontal bands. The waves appeared to have penetrated slightly up into the region of the O(^{1}S) layer at 96 km although they were heavily attenuated. The low level of stationary wave activity observed in the O(^{1}S) layer suggests that the wave energy associated with the waves was absorbed lower down, in a critical layer, in the 90–96 km altitude region. Eddy diffusion could also dampen the waves, and would act more effectively if the waves were propagating with a small or near-zero intrinsic phase speed.

[13] Wind profile measurements made from several radiosonde flights over South America were obtained from the University of Wyoming's, Department of Atmospheric Science website (http://weather.uwyo.edu/upperair/sounding.html). The wind profiles were obtained from ground level up to 30 km altitude every 12 hours. Three South American stations were used in the study; Santa Domingo (SD), Chile (33.6°S, 71.6°W) located on the western side of the Andes mountain range and at Cordoba (CO) (31.3°S, 64.2°W) and Santa Rosa (SR) (36.6°S, 64.3°W), Argentina on the eastern side. The locations are indicated in Figure 1.

[14] Typical examples of the radiosonde wind profiles during the period are shown in Figures 5a and 5b. The profiles are from the Santa Domingo radiosonde at 00 UT on 5 July 2008 and show a strong eastward wind flow (i.e., perpendicular to the Andes range) peaking in the upper troposphere near 12–13 km with values of reaching values of 60–80 ms^{-1}. Similar behavior was present in wind

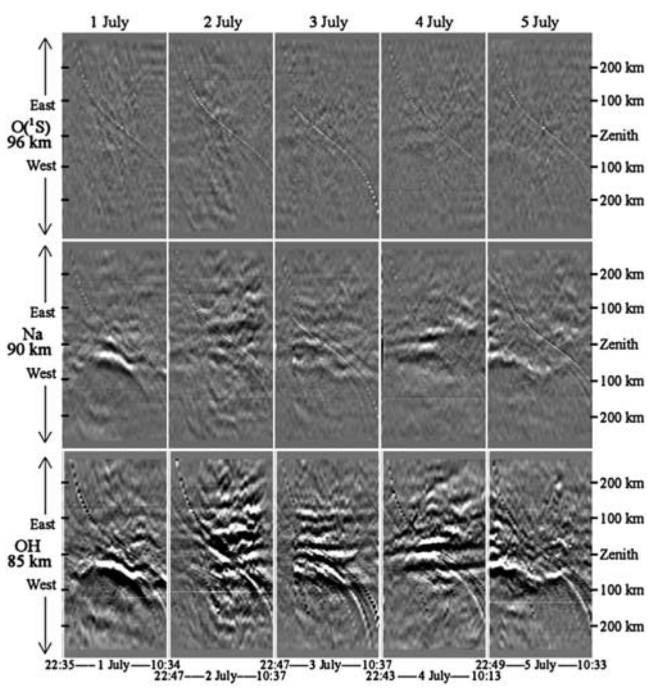

Figure 4. Time-history plots of the OH, Na, and O(^{1}S) nightglow emissions during the five nights of 1–5 July 2008. The generation of the plots is described in the text. Time runs horizontally and the spatial (East-West) dimension is in the vertical with eastwards directed upwards and westwards downwards. The central position of the Andes range would be aligned horizontally and positioned near the "100 km" line to the west of ELO. The stationary nature of the waves during the nights is clearly evident.

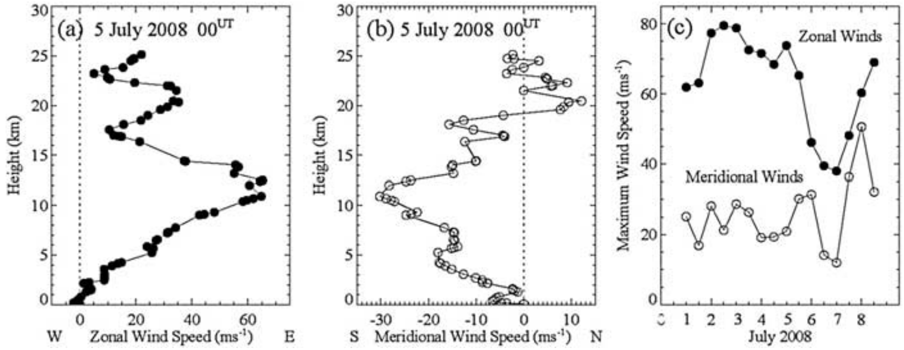

Figure 5. (a) Zonal and (b) meridional winds obtained from radiosonde measurements originating from Santa Domingo, Chile on 5 July 2008 at 12UT (see location in Figure 1). The zonal jet stream can be seen peaking near 14 km altitude. (c) Maximum zonal and meridional wind speed measured by the radiosondes at 12-hour intervals during the period of 1–8 July 2008. During that period, the height of the altitude of the maximum wind speed was relatively constant and occurred at about 13–15 km altitude.

measurements obtained by the Cordoba and Santa Rosa radiosondes during contemporaneous flights. Figure 5c shows the maximum zonal and meridional wind speeds measured by Santa Domingo radiosonde flights at 12 hour intervals during the 1–8 July 2008 period. The zonal winds were consistently very large compared to the meridional winds.

4. Discussion

[15] Several previous studies have reported gravity wave signatures near the South American Andes mountain range in tropospheric and stratospheric measurements, particularly from satellite measurements [e.g., *Eckermann and Preusse*, 1999; *Preusse et al.*, 2002; *Jiang et al.*, 2002; *Alexander and Teitelbaum*, 2007; *Alexander et al.*, 2008; *Spiga et al.*, 2008]. For example, *Jiang et al.* [2002] reported stratospheric air temperature (radiance) fluctuations over the Andes from measurements of the 33–53 km height region made with the Microwave Limb Sounder (MLS) aboard the Upper Atmosphere Research Satellite (UARS). The variance associated with the fluctuations increased markedly during the winter months of 1995 and 1996, and the increase was correlated strongly with intensity of the eastward tropospheric and stratospheric surface winds and with conditions associated with the generation and propagation of mountain waves. Contemporaneous temperature variance measurements obtained from several radiosonde station measurements in the Andes region (including two of the sites used in the present study, Cordoba and Santa Rosa) and averaged over 16–32 km altitude range showed a similar seasonal variation with a marked enhancement in the stratosphere during the winter months. The authors suggested that this was due possibly to mountain wave activity over the region. The observed scale-sizes of the mountain waves from the MLS measurements were 110 km and 400 km.

[16] Earlier modeling studies [e.g., *Schoeberl*, 1985; *Bacmeister and Schoeberl*, 1989; *Bacmeister*, 1993] and also in-situ studies [e.g., *Bacmeister and Gray*, 1990a, 1990b] have shown that orographically generated gravity waves can reach the middle atmosphere under the right conditions and propagation parameters.

5. Summary

[17] We report on optical imaging observations of mountain gravity waves occurring simultaneously in the mesospheric OH, Na and $O(^1S)$ nightglow emissions. The observations were made with the Boston University all-sky imager at the Eleoncito Observatory in Argentina during the period 1–8 July 2008. The stationary nature and nightly stability of the waves, together with their relative positions and orientation with respect to the Andes mountain range, were consistent with gravity waves that had been generated orographically and had subsequently propagated up into the mesosphere. The results presented here are, to our knowledge, the first unambiguous evidence of mountain gravity wave activity in the mesosphere. A more detailed and comprehensive analysis and study of the wave events will be undertaken in a future paper.

[18] **Acknowledgments.** Data analysis was supported by an NSF grant award ATM-0535453 for SMS and ATM- for JB and MM. The Boston University Airglow Facility at El Leoncito is supported by ONR Grant. We are grateful to the Director and staff of the El Leoncito Observatory (CASLEO) for their continued support of our work there. We also thank Larry Oolman (University of Wyoming) for providing the radiosonde data, and James Russell (Hampton University), Martin Mlynczak (NASA Langley Research Center), Larry Gordley (GATS, Inc.) and the SABER data processing team for providing the TIMED SABER data. We are most grateful for the helpful discussions from Juergen Scheer of I.A.F.E., Buenos Aires, Argentina.

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