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An unusual mesospheric bore event observed at high latitudes over Antarctica

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[1] All-sky CCD observations of short-period mesospheric gravity waves have been made from Halley Station, Antarctica (76°S, 27°W). On 27 May, 2001, an unusual wave event exhibiting several features characteristic of a "bore" was observed in the OH, Na, and O_2 nightglow emissions. Mesospheric bores are rare wave events that have previously been observed at mid- and low-latitudes. This event was particular interesting as: (1) it initially appeared as a single, high contrast, linear front, accompanied by a sharp enhancement in intensity in all three emissions, (2) a number of trailing wave crests were observed to form with a measured growth rate of 6.6 waves/hr, and (3) the wave pattern exhibited unusual dynamics with significant variability in the observed phase speed and a reduction in the horizontal wavelength by ~50% over a 1-hr period. The location of Halley and the observed propagation suggests a ducted wave consistent with current bore models. **Citation:** Nielsen, K., M. J. Taylor, R. G. Stockwell, and M. J. Jarvis (2006), An unusual mesospheric bore event observed at high latitudes over Antarctica, *Geophys. Res. Lett.*, *33*, L07803, doi:10.1029/2005GL025649.

1. Introduction

[2] *Taylor et al.* [1995] described a spectacular short-period gravity wave event observed in four mesospheric nightglow emissions from Hawaii during the ALOHA-93 campaign. The event was characterized by a sharp leading front followed by a series of phase-locked wave crests (horizontal wavelength λ_h = 19 ± 1 km, phase speed c_p = 76 ± 3 m/s) which exhibited a 180° phase reversal as observed in the near infrared OH emission (nominal peak height ~87 km) and the OI 557.7 nm emission (altitude ~96 km). Coincident intensity measurements showed the front was characterized by an abrupt increase in the OH brightness and a concurrent decrease in the OI emission. Later, *Dewan and Picard* [1998] suggested that this curious wave event exhibited characteristics expected of an internal undular mesospheric bore. Although bores are a well-known phenomenon and frequently occur in river estuaries, shallow seas, and in the troposphere, this was their first identification in the upper mesosphere. *Dewan and Picard* [1998], developed a simple model for bore propagation which invoked the presence of a mesospheric duct for sustaining the motion and they also provided a "checklist" for future identification of bores.

[3] Several bores have subsequently been reported at mid-latitudes. One event observed by *Smith et al.* [2003] over southern USA lasted for ~5.5-hrs and was visible to the naked eye. Later, *She et al.* [2004] observed a bore in the OH emission which appeared to be in transition from an undular to a turbulent, internal bore. In particular, coincident Na lidar confirmed the existence of a temperature inversion layer that may have served as a duct for the bore. Similarly, *Smith et al.* [2005] used temperature data from the SABER instrument on TIMED satellite to identify an inversion layer in the vicinity of a bore observed over Arecibo, PR. Most recently, *Fechine et al.* [2005] have reported a large number of mesospheric bore events (over 60) observed at equatorial latitudes (7°S) over a 3-yr period suggesting they are much more copious at low-latitudes.

[4] Another type of frontal disturbance termed a "wall" event has also been reported. Wall events are quite distinct from transient bores and have been associated with much larger-scale, longer-lived tidal features that induce significant perturbations in the airglow emission brightness, temperature and Na abundance [*Swenson et al.*, 1998].

[5] As part of a collaborative program with British Antarctic Survey, an all-sky (180°) airglow imager has been operated in Antarctica since 2000. The primary goal of this program was to study short-period gravity waves and their sources at southern polar latitudes. A large number (>400) of extensive short-period waves exhibiting horizontal characteristics (λ_h ~10–50 km and c_p ~10–80 m/s) have been observed to date with only ~5 potential bore candidates. The event presented here was the most prominent and unique in several aspects compared with previous reports in the literature. To our knowledge this is the first identification of a mesospheric bore at polar latitudes. Here we report the main characteristics of this event establishing its bore-like nature. A local spectral analysis technique has been used to investigate the dynamical properties of the event in detail [*Stockwell et al.*, 2006].

2. Observations and Results

[6] Measurements were made from Halley Station, Antarctica (76°S, 27°W) using an all-sky CCD imaging system similar in performance to the system used by *Taylor et al.* [1995] for the ALOHA-93 campaign. Sequential measurements of the NIR OH (715–930 nm) and O_2 (865.5 nm) bands, and the Na (589.2 nm) emission were made using exposure times of 15,90,120 s, respectively. Background sky measurements were also made at 572.5 nm to monitor for cloud cover. Observations were made using a repetition rate of 2-min for the OH data and ~6-min for the other emissions.

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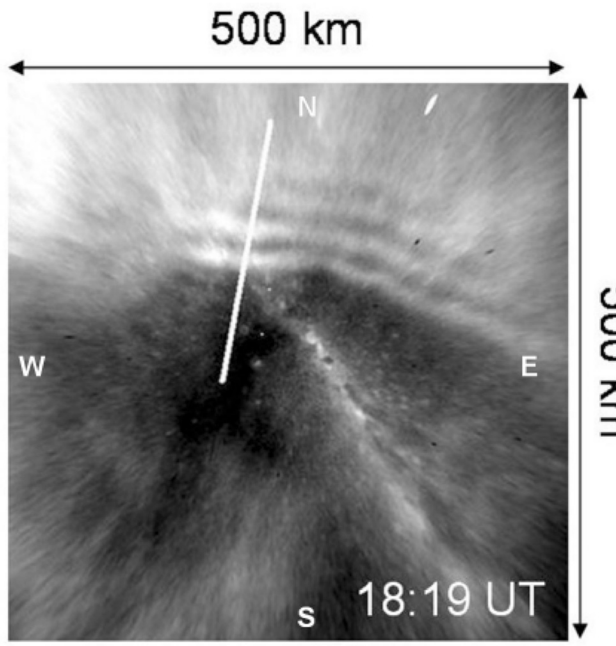

Figure 1. Wave event imaged in the Na emission showing leading bright front accompanied by three trailing crests propagating southward. The star field has been removed and the data were mapped onto a 500 × 500 km grid assuming an emission altitude of 90 km. The white line marks the location of the intensity data plotted in Figure 2.

[7] On 27 May, 2001, a prominent bore-like event was observed for ~3-hrs from 17:30 UT. The event entered the field of view from the north and was characterized by a single bright front in all three emissions. Around 18:05 UT a series of trailing wave crest began to grow. Figure 1 shows an Na image at 18:19 UT, when the wave train was already well developed. The primary direction of motion was almost due south (186° ± 5°N). The data have been analyzed using standard 2-D spectral analysis methods [e.g., *Garcia et al.*, 1997] and spatial mapping techniques to estimate the average horizontal wave parameters at hourly intervals (Table 1). Initially, the average c_p was 76 ± 5 m/s and λ_h was 30 ± 1 km (observed period ~6.5 min) in all three emissions. However, over the next hour the pattern slowed down to ~65 m/s and decreased its wavelength significantly to ~19 km. Around 19:30 UT, the number of wave crests had grown to ~12 but the intensity of the pattern had reduced significantly. By 21:00 UT the trailing waves had dissipated leaving a faint but still discernable leading front that later exited the field of view to the south.

Table 1. Hourly Averaged Horizontal Wave Parameters Derived From the Image Data[a]

Emission	Assumed Height	λ_h, km	c_p, m/s	T_{obs}, min	$\bar{u}$, m/s	$c_p - \bar{u}$, m/s	T_i, min
			18:00 UT				
OH	87	31	76	6.8	−28	104	5.9
Na	90	29	78	6.2	−34	112	4.3
O_2	94	28	73	6.4	−29	102	4.6
			19:00 UT				
OH	87	19	66	4.8	16	50	6.3
Na	90	18	63	4.8	10	53	5.7
O_2	94	19	63	5.0	−2	65	4.9
			20:00 UT				
OH	87	18	64	4.7	−3	67	4.5

[a]The intrinsic properties were estimated using available wind data. Only OH measurements were possible after 20:00 UT.

3. Discussion

[8] The main criteria for a mesospheric bore as described by *Dewan and Picard* [2001] are: the existence of a hydraulic jump initiating the bore perturbation, and the presence of a ducting medium in which it can propagate horizontally. An undular bore is characterized by growth in the number of wave crests with time while the hydraulic jump is thought to manifest itself in the airglow emissions as a sharp change in brightness at the leading edge of the perturbation. Figure 2 shows a scan of emission intensity across the wave packet for the OH, Na, and O_2 emissions at ~18:20 UT. The wave pattern was well developed and all three emissions were characterized by a sharp increase in brightness (around pixel 140) which coincided with the onset of the wave front. The fact that all three emissions increased in brightness is in contrast to the event observed by *Taylor et al.* [1995] and suggests a ducting region located above the emission layers rather than in between them [*Dewan and Picard*, 1998]. The associated wave crests show in-phase relation between the OH and Na data (due to their close proximity) but, a clear anti-phase (180°) relation with the higher altitude O_2 emission. This observation strongly supports a ducted wave motion where the phase reversal is due to the time and temperature dependencies of the emitting species [*Snively and Pasko*, 2005]. Furthermore, coincident measurements of the hourly averaged background wind field at Halley have been used to estimate the intrinsic properties of this wave (see Table 1) and its nature using the vertical wave number squared (m^2) to identify regions of Doppler ducting [*Isler et al.*, 1997]. On this occasion freely propagating and evanescent regions existed during the early observation of the bore both which later evolved with time. Unfortunately, we do not know the

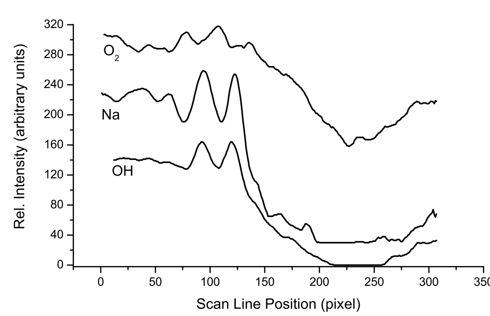

Figure 2. Plot showing intensity change with position across the observed wave front (see Figure 1). The location of each scan line has been adjusted to account for the different times of the consecutive observations in the three emissions. For clarity the intensity for each plot has been arbitrarily adjusted so that the emissions are ordered in altitude with O_2 being the highest. Note the OH and Na oscillations are in-phase while the O_2 structures are smaller in amplitude and 180° out of phase.

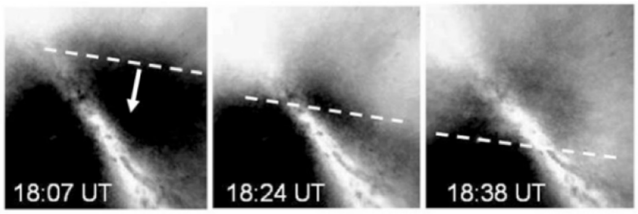

Figure 3. Filtered OH images showing the development of the intensity jump with time. The dashed line indicate the location and orientation of the leading wave crests progressing on an azimuth of 186°N. The bright diagonal feature is the Milky Way.

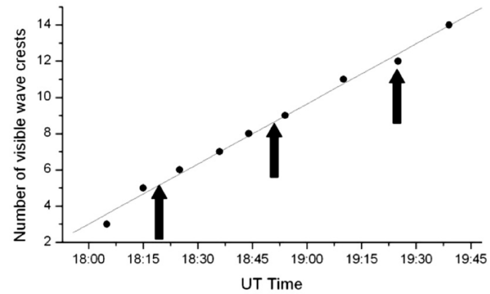

Figure 5. Plot showing the linear increase in the number of visible wave crests over a ~2-hr period (6.6 crests/hr). The arrows indicate the data times in Figure 4.

temperature structure during this event but a detailed analysis of the wind data is currently in progress.

[9] Figure 3 shows three snapshots of the event at ~15-min intervals with the wave packet removed using a temporal high-pass filter with a cut-off frequency of 0.00125-Hz. The intensity enhancement is quite evident progressing southward as indicated by the dashed line. This novel analysis clearly illustrates the basic nature of the underlying step-like perturbation and reveals that it propagated in the same direction (and with the same observed speed) as the associated wave pattern.

[10] A unique characteristic of an undular bore is the growth in the number of trailing wave crests with time which acts to dissipate its energy [e.g., *Dewan and Picard*, 1998]. This event exhibited remarkable wave growth during an ~2-hr period which is illustrated in the OH data of Figure 4. To better view the wave structure each picture is a difference image obtained by subtracting two adjacent images in time. At 18:20 UT six prominent crests were evident reducing in spatial extent and brightness toward the rear of the wave train. By 18:50 UT the number of wave crests had grown to 8 and their horizontal separation had reduced significantly. Note, the region behind the wave packet is clearly absent of any wave activity. Around 19:25 UT the wave pattern had evolved considerably: the leading crest was less coherent and much fainter with at least 12 trailing crests. Figure 5 plots the number of visible wave crests as a function of time. Nine measurements were made during this ~2-hr period indicating a remarkably uniform and high growth rate of 6.6 waves/hr, as indicated by the least squares linear fit to the data. Previous model and measured estimates of wave growth indicate a typical range of 1–3 waves/hr [*Dewan and Picard*, 1998; *Smith et al.*, 2003; *She et al.*, 2004; *Smith et al.*, 2005]. Our Antarctic measurements are therefore much larger than previously reported but the data strongly support the hypothesis that this event was a mesospheric bore observed at high-latitude. Furthermore, since this event first appeared as a single bright front propagating into our field of view we have essential witnessed the onset of the wave growth but not the "birth" of the bore itself. It is therefore not possible to determine the lifetime of the event using the wave growth rate as postulated by *Dewan and Picard* [1998].

[11] The origin of this bore event is not yet known. *Dewan and Picard* [2001] proposed that the interaction of gravity waves with the mean flow at a critical layer may generate mesospheric bores. In order for this to happen, they concluded that the gravity wave source must be relative local and unusually strong, examples given were thunderstorms, orographic forcing, and possibly the auroral electrojet at high latitudes. However, on this occasion it is not thought that the auroral electrojet was a viable source for this event due to the only moderate magnetic activity, ($K_p \sim 4$), and the observed poleward direction of wave motion suggesting a lower atmospheric source. *Smith et al.* [2003] attributed the origin of the bore event they observed over southern USA to a large cold front at a range of over 1000 km. Most recently, *Smith et al.* [2005] have shown how the breaking of a large-scale mesospheric gravity wave event may lead to an undular bore. Possible source regions near Antarctica have been identified by *Wu and Jiang* [2002] using stratospheric measurements from the UARS satellite. They observed a peak gravity wave activity over

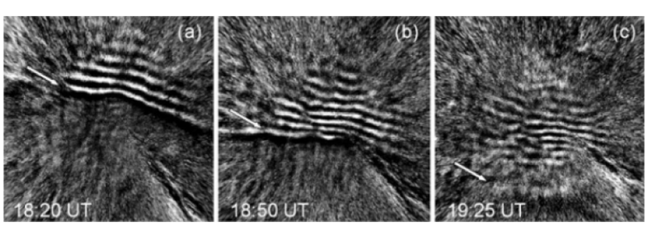

Figure 4. OH difference images showing the development of the wave field at three instances separated by ~30 min. (a) Number of crests, n = 6, c_p = 76 m/s, and λ_h = 31 km, (b) n = 8, c_p = 66 m/s, λ_h = 19 km, and (c) n = 12, c_p = 64 m/s, and λ_h = 18 km. The arrows show the location of the leading front which is less contrasted in Figure 4c.

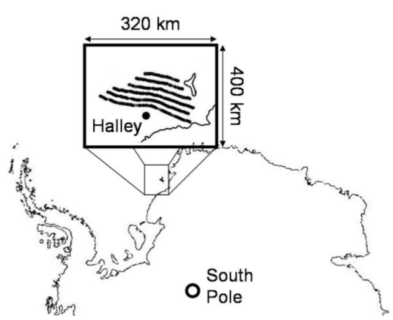

Figure 6. Enlarged map showing the location of the OH wave pattern at ~18:25 UT as it approached the Antarctic coast (heading 186°N).

the Drake Passage and the Antarctic Peninsula region. In addition, they reported enhanced coastal gravity wave variances in close proximity to the edge-region of the Antarctic polar vortex. Figure 6 shows an enlarged map of the OH bore wave field at 18:25 UT. The location, orientation, and direction of motion are not consistent with wave generation in vicinity of the Antarctic Peninsula which lies well to the west of Halley. Furthermore, the overwhelming majority of the short-period gravity waves observed from Halley exhibited a strong meridional motion toward the Antarctic continent suggesting source regions equatorward of Antarctica. To help identify the source, we have investigated composite infrared satellite image centered on Antarctica for May 27, 2001 at 15:00 UT which show several well-spaced cyclones surrounding the continent. Of particular interest, is a cyclone located ~2000 km equatorward of Halley. Although well situated this potential source is clearly at too large a range for detection of freely propagating short-period waves at mesospheric heights over Halley. However, ducted waves can travel large distances horizontally [e.g., *Pautet et al.*, 2005]. Assuming a constant c_p of ~76 m/s (as initially observed) a propagation time of 7-hr would be needed for the bore to traverse a 2000 km horizontal path, which is well within the lifetime of the observed cyclone. Thus, the bore might have resulted from cyclonic activity but the evidence is only circumstantial.

4. Summary

[12] An unusual short-period gravity wave event was detected over Antarctica on May 27, 2001. The event was characterized initially by a single front that evolved with time, generating a series of phase-locked wave crests that grew to over 12 in number (growth rate of 6.6 waves/hr). The crests then dissipated and the leading front was observed to continue its southward motion but with a much reduced optical signature. This event is most consistent with a ducted mesospheric bore and our analysis clearly illustrates the underlying nature of the hydraulic jump as proposed by *Dewan and Picard* [1998]. Previous reports of bore-like events have all been made from mid and low-latitudes where mesospheric inversion layers are known to be a relatively common occurrence. In contrast, mesospheric temperature inversions appear to be a rare phenomenon at polar latitudes [*Cutler et al.*, 2001]. This may account for the very low number of potential bore observations (~5) that we have obtained over the past 4 winter seasons in Antarctica. A possible source for this event was strong cyclonic activity equatorward of Antarctica. This wave event also exhibited highly unusual dynamics with significant changes in the horizontal wavelength with time. This may have resulted from systematic variations in either the depth of the duct or the mean height of the bore above the top surface of the duct.

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