GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 20, PAGES 2833-2836, OCTOBER 15, 1995

All-sky measurements of short period waves imaged in the OI(557.7 nm), Na(589.2 nm) and near infrared OH and $O_2(0,1)$ nightglow emissions during the ALOHA-93 campaign

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Abstract. As part of the ALOHA-93 campaign a high performance all-sky CCD imaging system was operated at Haleakala Crater, Maui, to obtain novel information on the properties and sources of short period gravity waves over an extended height range ~80-100 km. Sequential observations of the near infrared OH and $O_2(0,1)$ bands and the visible wavelength OI(557.7 nm) and Na(589.2 nm) line emissions have enabled a unique comparison of the morphology and dynamics of the wave motions and their occurrence frequency at each emission altitude to be made. Two major findings are: (a) the detection of significantly higher amounts of wave structure at OI altitudes (~96 km) compared with that in the OH emission (~87 km) and (b) the discovery of an unusual morphology, small-scale wave pattern that was most conspicuous in the OI emission and essentially absent at OH heights. These data provide strong evidence for the presence of ducted wave motions in the lower thermosphere.

Introduction

The naturally occurring nightglow emissions provide an excellent medium for the remote sensing of short period (<1 hour) gravity waves in the upper mesosphere and lower thermosphere. In particular, image data give unique information on the two-dimensional horizontal parameters of these waves. To date, most imaging studies have been made of the bright near infrared (NIR) hydroxyl (OH) band emissions which originate from a well defined layer centered at ~87 km. Occasional observations have also been made of the NIR $O_2(0,1)$ At band (peak altitude ~94 km) [Hecht and Walterscheid, 1991] and the visible wavelength OI(557.7 nm) line (peak altitude ~96 km) [Armstrong, 1982], while measurements of the faint Na(589.2 nm) D lines (peak altitude ~90 km) are exceptionally rare [Taylor et al., 1987]. Measurements of more than one nightglow layer are uncommon, yet they provide a simple and powerful tool for exploring the propagation of gravity waves over an extended height region in the vicinity of the mesopause [Noxon, 1978; Taylor et al., 1987]. For the ALOHA-93 campaign a novel imaging system was developed to investigate the morphology and dynamics of gravity waves that existed in the ~80-100 km height range.

Instrumentation

The monochromatic imaging system utilized a bare (1024 x 1024 pixel) charged coupled device (CCD) of high quantum efficiency (~80% at visible, 50% at NIR wavelengths). The large dynamic range and low noise characteristics (dark current <0.5 e^-/pixel/sec) of this device provided an exceptional capability for quantitative measurements of faint, low contrast (<5%) gravity waves. The camera used a fast (f/4) all-sky (180°) telecentric lens system and a five position filter wheel. Table 1 lists the filter characteristics and exposure times. Four emissions were measured: the NIR OH and $O_2(0,1)$ bands and the OI (557.7 nm) and Na (589.2 nm) lines. A background measurement (Bg) was also made at 572.5 nm to aid the analysis of the visible wavelength data. The exceptional sensitivity of the imager enabled sequential measurements at a high repetition rate of 3-5 min for the OI emission and ~9 min for the other emissions.

Paper number 95GL02946
0094-8534/95/95GL-02946$03.00

Observations and Results

Observations were made from 6 to 23 October, 1993 from the DOE Facility, Haleakala Crater, Maui (20.8°N, 156.2°W, 2970m). The weather conditions were good but deteriorated around the new moon. Nevertheless, excellent image data were obtained on ten nights and limited observations on a further four occasions. In total nearly 6,000 images were recorded.

Wave Morphology and Dynamics

Well-defined wave patterns were observed in all four nightglow emissions. Comparison of these data sets reveals that the most commonly imaged structure consisted of extensive, large-scale waves, termed "bands", which are generally believed to be the signature of freely propagating short-period (<1 hour) gravity waves [Taylor et al., 1987]. Although reports of multiple wave events are relatively rare, complex wave patterns consisting of two or more band events were routinely observed, especially in the OI emission. Several examples of wave structure are given in Figure 1. Figure 1a shows two near orthogonal band patterns imaged in the OI emission on 22

Table 1. Filter details and exposure times for the imager.

Filter	Wavelength (nm)	Bandwidth (nm)	Transmission (%)	Integration Time (sec)
OI	557.7	2.65	~83	90
Na	589.1	2.5	~80	120
Bg	572.5	2.67	~83	90
$O_2(0,1)$	865.5	12.0	~85	90
OH*	715-930	215	~80	20

* with a notch at 865 nm to suppress the $O_2(0,1)$ emission

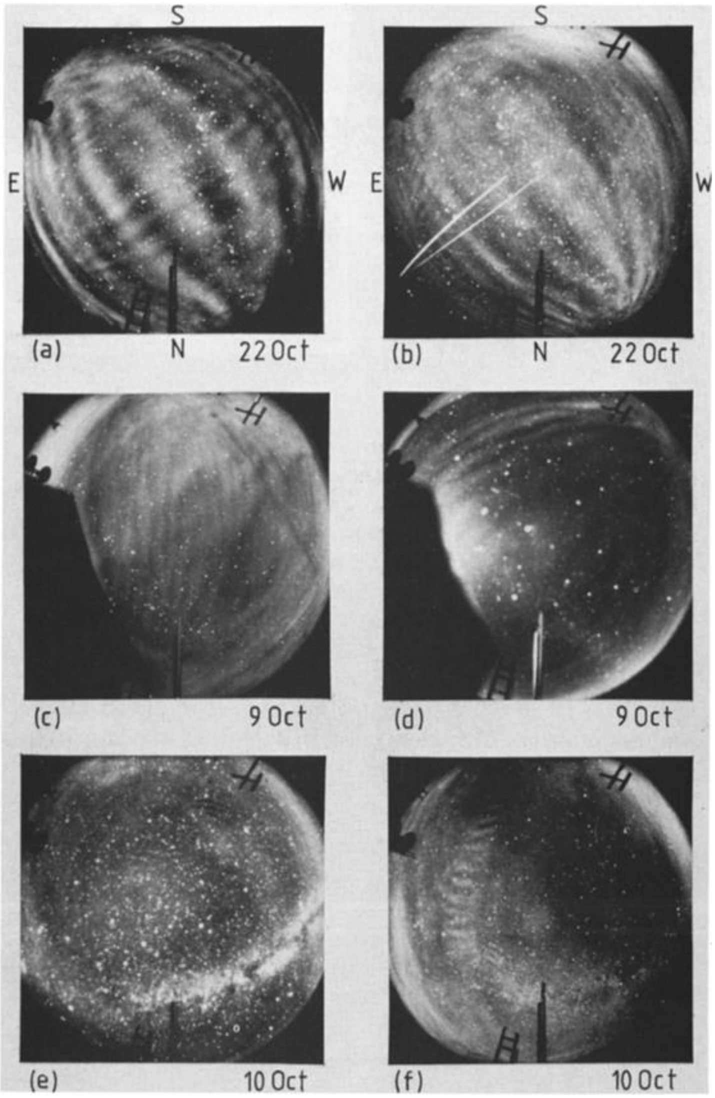

Figure 1, Images a-d show four examples of gravity wave "band" structure: (a) is an OI image recorded on 22 October at 14:45 UT, (b) is an Na image taken on the same night as 'a' but at 12:44 UT (note the bright lines show the University of Illinois Na lidar beam pointing at two azimuths during the 120s exposure), (c) is a complex OI image recorded at 11:28 UT on 9 October and, (d) is an O_2 image on the same night as 'c' at 13:24 UT. The shield in images 'c' and 'd' blocks out the rising moon. Image (e) shows an isolated NIR OH ripple event (top right of image) recorded on 10 October at 09:00 UT. Finally, (f) shows a new wave pattern consisting of a row of short wavelength waves imaged in the OI emission on the same night at 'e' as 09:30 UT.

October. The prominent wave progressing towards the SW was conspicuous in all four emissions (indicating that it extended throughout the ~80-100 km region), but the fainter wave progressing towards the NW was evident only in the higher altitude emissions. This is illustrated in Figure 1b which shows the same wave field imaged in the Na emission ~2 hours earlier. The dominant SW-ward wave motion is clearly seen but there is very little evidence of the second, orthogonal wave pattern. This situation arose often during the campaign indicating that a significant fraction of the waves exhibited ducted or evanescent behavior rather than freely propagating characteristics (i.e. they existed over only a restricted height interval). The horizontal parameters of these wave motions are given in Table 2.

Table 2. Horizontal wave parameters for the images of Figure 1.

Fig. 1	Emission	Height (km)	Time (UT)	Heading	λ_h (km)	v_h (ms^{-1})	T_{obs} (min)
(a)	OI	96	14:45	SW	38	34	19
(a)	OI	96	14:45	SE	19	40	8
(b)	Na	90	12:44	SW	36	27	22
(c)	OI	96	11:28	E	10	61	2.7
(c)	OI	96	11:28	NE	16	80	3.4
(c)	OI	96	11:28	SE	22	40	9
(d)	O_2	94	13:24	SE	25	37	11
(e)	OH	87	09:00	-	11	-	-
(f)	OI	96	09:30	N	12	53	3.9

An even more complex OI wave display is shown in Figure 1c which was recorded on 9 October. The contrast of the structures is not as high as in the previous image but at least three band-type motions progressing in markedly different directions can be distinguished. The predominant wave motion consisted of a large number (>12) of well formed, N-S aligned bands of short horizontal wavelength (~10 km) moving eastwards. The leading crests of the second set of waves (evident to the SW) exhibited pronounced curvature (Figure 2) suggesting a "point-like" wave source. (Note, these waves appear linear in the image due to the all-sky format.) The third wave pattern consisted of a set of faint bands (that are visible near the zenith and at low elevations to the NW) progressing towards the SE. While the first two wave motions were present primarily in the OI emission, these bands were evident in all four emissions. Figure 1d shows this wave motion in the O_2 emission ~2 hours later. The three leading O_2 wave crests are also plotted in Figure 2 and show similar horizontal scale sizes to the OI bands but the wave field has rotated ~20° during the intervening period. These measurements indicate wave generation by three distinct sources, however, only the SE-ward wave motion exhibited extensive vertically propagating characteristics.

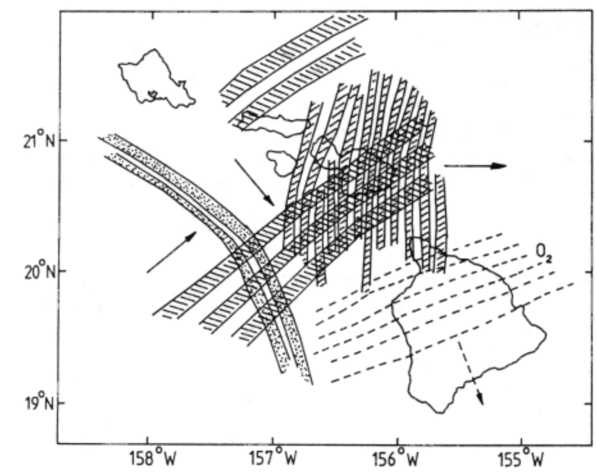

Figure 2. Map showing the geographic positions and scale sizes of the three OI wave motions evident in Figure 1c (assuming an emission height of 96 km). For comparison some of the O_2 data of Figure 1d are also plotted (assuming a height of 94 km).

In contrast to the band measurements, Figure 1e shows an example of a small-scale wave event termed a "ripple". Ripples are quite distinct from bands, exhibiting short horizontal wavelengths (typically 5-15 km) and extending over much smaller geographic areas. The ripples in Figure 1e were imaged in the OH emission and are typical of an isolated event lasting <30 min. However, ripples were also observed to occur in the presence of much larger-scale bands with no apparent association. An important new result of our ALOHA-93 measurements is that ripples were rarely (if ever) observed in all four emissions at the same time.

On several occasions we detected a novel morphology wave pattern which outwardly resembled a ripple event but which was considerably larger in spatial extent and had a much longer lifetime. Figure 1f is an example of this type of wave pattern. The image is dominated by a set of small-scale waves consisting of many crests (>14) aligned in a row. Occasionally these waves would appear as a single row (as in this image), but they were most often seen in groups of two or more rows, oriented in the same general direction and dispersed over a large area of sky. The apparent width of the rows was restricted to typically <50 km but their overall length spanned hundreds of kilometers. In this example the horizontal wavelength (λ_h) of the waves was 12 km (Table 2) and the row length >160 km. These unusual patterns were imaged on several occasions and were most conspicuous in the OI emission, less contrasted in the O_2 and Na emissions and were rarely imaged at OH wavelengths suggesting ducted wave motions. A detailed investigation of these patterns is presented in Taylor et al. [1995].

Frequency of Occurrence

Histograms of the frequency of occurrence of structure for each emission are given in Figure 3. The shaded areas indicate the amount of time that structure of any type (primarily bands) was detected somewhere within the camera's field of view (>600,000 km^2). The solid areas indicate the fraction of that time that small-scale structure, mainly in the form of ripples, was imaged. The total clear sky observing time for each emission was similar at ~80 hours, but as already indicated, theamount and type of structure detected in each emission varied considerably from night to night. Structure was most frequently imaged in the OI emission at ~95% of the observing time, and least frequently in the OH and O_2 emissions at ~57%. Likewise, ripples were most common in the OI emission (57% of structure time), while the OH and O_2 emissions again showed the lowest occurrence frequency (19% and 25% respectively). Of considerable surprise was the fact that wave structure was routinely detected in the faint Na emission at over 70% of the time, of which 35% was in the form of small-scale waves.

For most of the time the OI and Na emissions exhibited considerably more structure than the OH emission suggesting a preponderance for ducted (or evanescent) waves in the higher altitude emissions. However, from 18-22 October all four emissions showed similar wave activity with band structure detectable for much of the time suggesting a change in the prevailing conditions towards freely propagating waves. Observations of structure in the O_2 emission were anomalously low (compared with that in the OI emission) throughout the campaign.

Discussion

Data gathered during ALOHA-93 reveal a wealth and diversity of wave structure throughout the upper mesosphere and lower thermosphere showing that short period gravity waves are commonplace over the mid-Pacific ocean. Surprisingly, the occurrence of wave structure was considerably higher in the OI (>35%) than in the OH emission which was similar to previous measurements [Taylor and Hill, 1991]. As observations of the visible wavelength emissions are relatively rare, it is not known whether this situation was atypical. Recent measurements using the same imager at Bear Lake Observatory, Utah (41.6°N) also indicate a significantly higher occurrence of OI wave structure on many nights. This result provides persuasive evidence for the existence of ducted short period wave motions in the higher

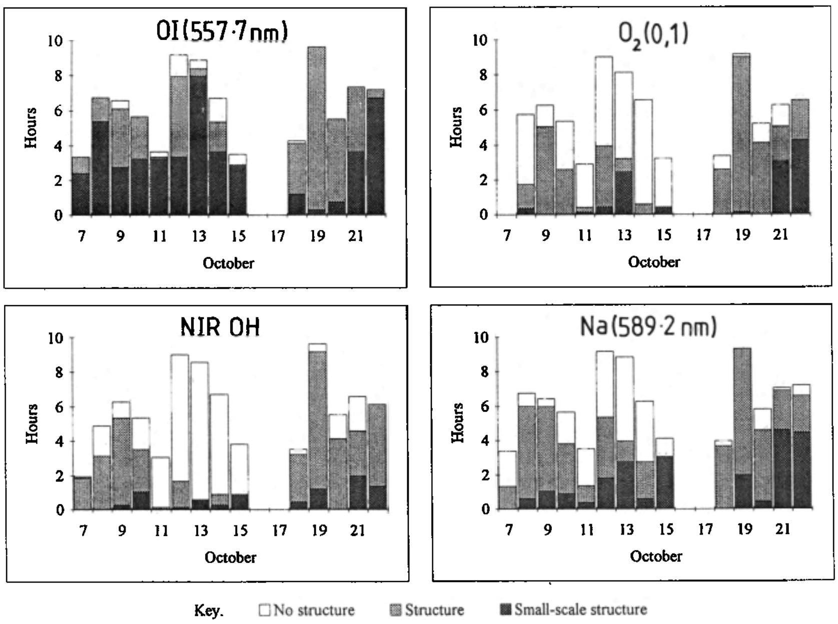

Figure 3. Frequency of occurrence of wave structure in each nightglow emission. No data were obtained on 16 and 17 October due to bad weather.

altitude emissions. These waves may have originated in distant tropospheric weather disturbances or alternatively they may have been generated in the upper atmosphere by the breakdown of large-scale motions possibly of tidal origin. An assessment of the relative percentage of ducted versus freely propagating short period waves is important (but has yet to be made) as ducted waves propagate over much larger horizontal distances before they impart their momentum into the background medium.

It is also possible that gravity waves may have been more easily detected at OI altitudes (~96 km) due to their growth in amplitude with height (assuming no dissipation). The higher occurrence frequency for Na structure (~90 km) compared with OH structure is consistent with this idea. However, images of the O_2 layer (which exists in close proximity to the OI emission at ~94 km) exhibited much less wave structure (similar to that of the OH emission) and do not support this notion. This point together with numerous observations of extensive, band-type displays in the OI emission that were essentially absent in the OH emission, indicates that other important factors, such asducting, can affect significantly the abundance of waves in the higher altitude emissions. Indeed, the short observed periodicities of many of the wave motions discussed here (Table 2) are close to the local Brunt-Väisälä period (~5 min) and are therefore susceptible to ducting in the vicinity of the mesopause.

Small-scale wave motions in the form of ripples were observed in abundance on some nights but were virtually absent on other nights. On several occasions OI ripple patterns were also observed simultaneously in different areas of sky but at acute angles to each other. Together with the fact that ripples were rarely observed simultaneously in all four emissions these observations provide strong support for the hypothesis that ripples are generated in-situ over a limited height range by short-lived velocity shears [Taylor and Hapgood, 1990].

The detection of a novel, row-like, wave pattern has prompted considerable interest. The elongated morphology of the rows of waves is a characteristic that clearly discriminates them from other small-scale "ripple" events. These patterns tended to occur on nights when there was marked gravity wave activity in the form of extensive bands and they often appeared to be aligned orthogonal to the larger scale waves. However, it is not thought that they are the signature of large-scale gravity waves breaking as their horizontal wavelengths (typically 10-20 km) are too large and their lifetimes (>1 hour) too long to result from such an instability [Fritts et al., 1993]. One possible explanation of this type of wave pattern, based on the interference of two ducted short-period band motions exhibiting similar characteristics, but slightly different propagation headings, is discussed in Taylor et al. [1995].

In summary, the CCD imager developed for this campaign has proven to be exceptionally sensitive, providing an abundance of data on short-period wave motions particularly at visible wavelengths. Initial analysis of these data have revealed:

1. copious amounts of wave structure in the OI emission,
2. first detailed image measurements of Na wave structure,
3. different occurrence frequencies for waves in each emission,
4. evidence of ducted, as well as, freely propagating waves, and
5. a novel type of ducted wave pattern, mainly at OI heights.

Acknowledgments. We are grateful to J.A. Albetski, ThermoTrex Corp., for arranging our use of the DOE Facility. Funding for this program was provided by National Science Foundation, Grant No. ATM-9302844. Partial support for the data analysis was provided by the Geophysics Directorate, Air Force Phillips Laboratory, contract No. F19628-93-C-0165 as part of the SOAR program.

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(Received December 1, 1994; revised August 24, 1995; accepted August 28, 1995)