GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 17, PAGES 2211-2214, AUGUST 15, 1996

Seasonal dependence of mesospheric gravity waves (< 100 km) at Peach Mountain Observatory, Michigan

Q. Wu and T. L. Killeen

Space Physics Research Laboratory, Department of Atmospheric, Oceanic, and Space Sciences, The University of Michigan, Ann Arbor, Michigan

Abstract. We present results from a 14-month study of all-sky camera observations of the Hydroxyl (OH) nightglow made at the Peach Mountain Observatory, Michigan (42.3°N; 83.7°W). Spatial variations in the observed OH airglow images have been used to assess gravity-wave (GW) occurrence frequency at ~85 km altitude as a function of season. A strong seasonal dependence of mesospheric GW activity is observed, with peak activity in the summer months and much reduced activity during the winter months. Gravity waves (as defined by observed coherent variations in relative OH brightnesses of >~7.5) were found to be present on about 70% of the clear-sky nights during the summer months. During the spring, fall, and winter months, however, the observed GW occurrence frequency was very low (<10%). Most of the GWs were observed to propagate towards the eastward hemisphere. We suggest that the tropospherically-generated GWs are anisotropic (eastward) thus passing through to the mesosphere only in the summer and being filtered out by the intervening neutral winds during other seasons. It is also possible that the GWs are able to reach higher altitudes without breaking because of their smaller amplitudes at lower altitudes during the summer season relative to the winter season.

1. Introduction

Gravity waves (GWs) that propagate upwards and break at mesospheric altitudes are known to have a profound influence on the structure and dynamics of the middle atmosphere [*Fritts et al.*, 1993]. Ground-based all-sky camera (ASC) imaging systems have recently been used to study GWs in the nighttime mesosphere through measurements of the hydroxyl (OH) emissions at ~85 km altitude [*Taylor et al.*, 1991; 1993; *Swenson and Mende,* 1994]. Most of the previously reported ASC optical measurements, however, have been of the "case study" type. Thus, the available statistical information on mesospheric GWs has come from long-term medium frequency (MF) radar observations [*Manson and Meek,* 1988; *Meek et al.*, 1985; *Nakamura,* 1991], Na lidar observations [*Senft and Gardner,* 1991], and low frequency radio wave absorption measurements in the ionosphere [*Lastovicka et al.*, 1993].

Meek et al. [1985] summarized MF radar GW observations made in 1981 at Saskatoon (52°N). They studied waves in three different spectral ranges (periods between 48-8 hours, 8-1 hours, 1 hour to 10 min) in the 60-110 km altitude range. They noted that GWs in the spectral range of 10 min to 1 hour have a strong seasonal variation. The measured power spectral density (2.0 dB) was higher in the summer when the zonal wind was westward in the altitude range from 80 to 100 km (1.5 dB in the winter). *Nakamura* [1991] examined the spectral range from 5 min to 2 hr and obtained similar results. *Senft and Gardner* [1993] summarized nearly 5 years of Na lidar measurements taken at Urbana (40°N; 88°W). They measured Na layer density perturbations with periods from 20 min to 4 hrs and found that the greatest perturbations during the summer months of May and June (above 9%). On the other hand, by monitoring the LF radio wave absorption by the lower ionosphere, *Lastovicka et al.* [1993] were able to infer the GW activity in Europe at Pruhonice (49.45°N; 16.05°E). At first their data appeared to show a seasonal variation with strong activity in the summer, but later they attributed it to an artifact of the varying length of nighttime during different seasons.

Garcia and Solomon [1985] developed a two-dimensional dynamical/chemical model that includes a parameterization of GW drag and diffusion. By using this model, they estimated values for the eddy diffusion coefficient, which reflects the GW activity for different seasons. They noted that the derived coefficient was larger in the summer than in the winter above the altitude of 80 km, in accord with the MF radar and the Na lidar observations but inconsistent with the LF radio absorption measurements mentioned above.

Since there are still some inconsistencies in the past observations, it would clearly be desirable to compare observed GW characteristics from the optical imagery (ASC) with various other techniques such as radar, lidar, and LF radio absorption, with a view to extending the coverage in both time and space and to further validate some of the early results. Relatively inexpensive ASC systems can be automated and deployed at locations where radar and lidar coverage is impracticable. Also, ASC systems can readily provide horizontal spatial and phase velocity information. In this paper, we present first results of a long-term ASC OH nightglow observation program at Peach Mountain Observatory (PMO), Michigan (42.3°N; 83.7°W).

We focus on the observed seasonal dependence of the occurrence frequency of the mesospheric GWs at ~85 km altitude. In Section 2 we briefly describe the instrument, the data analysis scheme, and the observations from the time period March 1993 - May 1994. The results are then discussed in Section 3 and principal findings summarized in Section 4.

2. Observations

The ASC camera at PMO utilizes a thermoelectrically cooled bare Kodak CCD (KAF1400 1317x1035) detector. The CCD images are binned (2x2) and digitized by a 12 bit A/D converter. The camera uses an all-sky lens system (Nikon

Paper number 96GL02168
0094-8534/96/96GL-02168$05.00

fish-eye lens 170° field of view) to form an image of the sky on a 75 mm diameter filter. The imager is telecentric, with a ray cone angle of 7° at full aperture. The ASC design is described in more detail by *Mende et al.* [1977]. The filter consists of a notch filter (centered at 865 nm with bandwidth of 20 nm, minimum transmission 2.5%) coated on top of colored glass RG715 (90% transmission above 700 nm). The notch filter blocks the O_2 (0-1) emissions and the colored glass removes the visible emissions. The CCD quantum efficiency is ~40% near 700 nm and drops to 0% at 1000 nm, cutting off any emissions above that limit. The total OH nightglow emission brightness in the 700-1000 nm range is ~ 7.9 kR and the background is ~6.0 kR, based on the OH Meinel Band intensities [*Llewellyn et al.,* 1978] and airglow spectrum background [*Broadfoot and Kendall,* 1968]. The background emission increases from ~ .14 R/Å at 700 nm to ~8.0 R/Å at 1000 nm. The expected signal and background levels were estimated by convolving the OH emission intensity and background level with the CCD quantum efficiency curve and the filter transmission function over the spectral range from 700 nm to 1000 nm. An integrated expected OH signal of ~1.0 kR and a background of ~.52 kR were subsequently obtained.

The ASC started routine (automated) nocturnal observations on March 15, 1993. The sampling rate was typically one image every three minutes. We have visually reviewed the images taken during the time period from March 15, 1993 to May 31, 1994 (except for the month of January, 1994 when the instrument was not operational). At least one image every 30 minutes has been examined visually for the presence of GWs. More than 3500 images have been examined in this way. We estimate that the visual examination can detect relative variations in the total signal (including IR background and OH emissions) larger than ~5.0%, which is equivalent to ~7.5% relative variation in the OH emissions. The study time period was divided into 1-hour sections. Any 1-hour section during which the moon was above the horizon or the cloud coverage was > ~50% was discarded. Each 1-hour section was flagged for GW presence only if two consecutive images 30 minutes apart showed GW activity. Examples of flat-fielded ASC images with and without GW activity are shown in Figures 1a and 1b, respectively. For Figure 1a, the observed GW front was aligned nearly in the east-west direction. By looking at consecutive frames, the GW propagation direction was determined to towards the north-east direction.

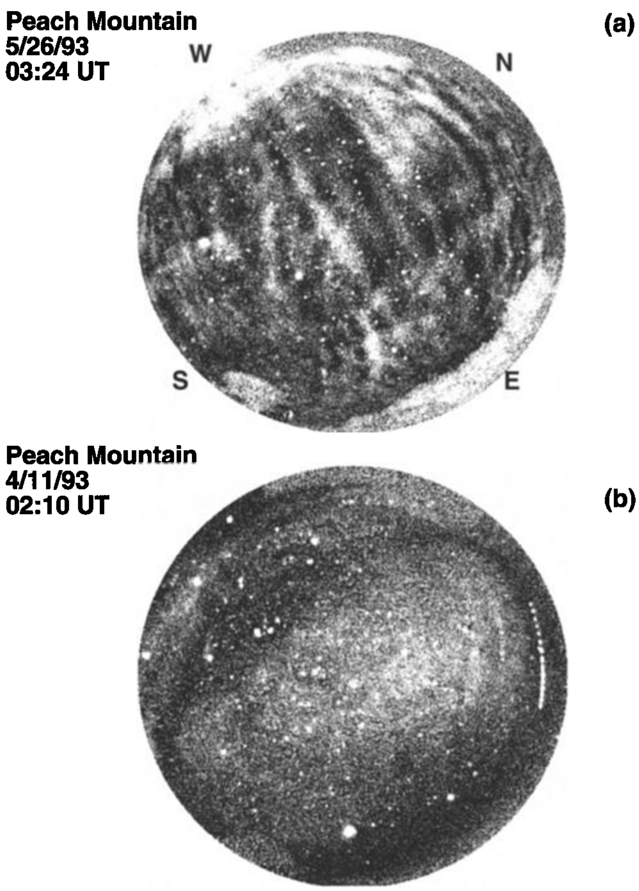

Figure 1. OH nightglow images taken by the ASC with (a) and without (b) GW activity. The images have been flat-fielded by measured backgrounds to remove the van Rhijn effect. In Figure 1a the GW was moving northeast and many stars were visible. The image was recorded on May 26, 1993 at 0324UT. The image in Figure 1b was taken on April 11, 1993 at 0210 UT and the image field was relatively uniform (bright signatures are due to stars and an aircraft passage).

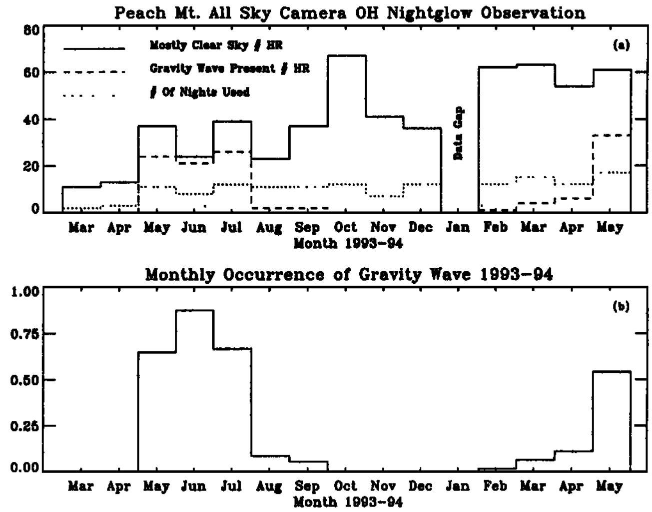

Figure 2. Statistical results of the GW occurrence frequency observed by the all-sky camera. Figure 2a shows the hours of mostly clear sky (solid line) and GW presence (dashed line). The dotted line denotes the number of nights when clear sky observations were made during each month. The GW occurrence frequency (defined by relative variations in OH brightness of > ~7.5%) is plotted in Figure 2b.

Figure 2a presents the number of hours of favorable observing conditions (no moon light and cloud cover less than 50%, solid line), and the number of hourly sections with GWs present (dashed line) on a monthly basis for the study period. The number of hours of favorable observing conditions and the number of clear-sky nights per month are also shown. The data coverage was relatively poor in March and April 1993 compared to other months. However, the March and April (1994) observations yielded a large number of nights of good observations. The GW occurrence frequency (the ratio of the number of hours with moonless mostly clear sky and the number of hours with GW presence) is plotted in Figure 2b. The majority of the observed GW activity occurred during the months of May, June, and July. The occurrence frequency reached ~70% in July 1993. GWs with amplitudes greater than our threshold occasionally appeared in August, September 1993 and February, March April, 1994 and none were found in the other months.

It should be emphasized again here that zero GW occurrence does not necessarily mean the complete absence of GWs since our technique employed has a sensitivity limited to ~7.5% relative variations in the OH airglow. If there are GWs during other seasons, however, they must lead to very weak variations in OH intensity over the Peach Mountain location.

It might be expected that large seasonal changes in overall OH brightness would lead to an erroneous determination of seasonal GW activity. In order to assess the magnitude of this potential problem, we have examined long-term OH brightnesses measured using the PMO Bomem Michelson interferometer during the same time interval and see variations in intensity of the order of 30%, with summer and winter peaks (R. J. Niciejewski, private communication, 1995). These brightness variations are considered too small to affect the conclusions of the present paper. The data from the Spring of 1994, indicating high GW activity reappearing in May, imply that the seasonal behavior shown in Figure 2b repeats from year to year.

An eastward bias for the directionality of the observed GWs was established by visually inspecting the nightly data on a frame-by-frame basis. This inspection revealed a clear tendency of the waves to propagate into the eastward hemisphere. We estimate that at least 70% of the observed GW wave fronts propagated into the Eastward Hemisphere

3. Discussion

The strong seasonal variation of the GW occurrence frequency is consistent with earlier radar observations at higher latitudes (Saskatoon, 52° N; 107°W) by *Meek et al.* [1985] and the Na lidar measurements (Urbana, 40° N; 88° W) by *Senft and Gardner* [1991]. *Meek et al.* [1985] reported that the zonal wind spectral intensity for such short period oscillations also had a strong seasonal dependence at 85 km altitude (greater in the summer than in the winter). Since the Na lidar showed the seasonal variation of GWs only in the zenith direction, *Senft and Gardner* [1991] were only able to speculate that the lidar-measured GWs might be anisotropic (mostly eastward propagating), based on mid-latitude wind directions from radar measurements, which showed westward winds in the summer and eastward in other seasons. *Meek et al.* [1985] observed that the intensity of GW-related oscillations in the zonal wind at 85 km during the summer season (May, June, and July) was above 3 dB (~ 14 m/s amplitude), while the mean zonal wind was in the range from 30 to 40 m/s. Similar intensities were observed at somewhat lower latitudes (Shigaraki, 35°N; 138°E) by *Nakamura* [1991] for the spectral range from 5 min to 2 hr.

Compared to the Na lidar measurements, it is interesting to note that the highest nightly average atmospheric density perturbation (above 9%) was reported by *Senft and Gardner* [1991] in their May and June data. The nightly average perturbations during other months were below 9%. This 9% perturbation deduced from Na emissions is very close to our 7.5% OH variation threshold. Thus, it appears that the strong perturbation measured by the lidar is consistent with the high occurrence frequency of GWs observed by the PMO ASC during the months of May and June. Despite the short distance between Urbana and Peach Mountain (~370 km) and similar latitudes (~40° N), there remains a discrepancy for the month of July. Since the data were taken during different years, this discrepancy is probably not serious. The relatively good agreement among the seasonal trends of GW activity obtained using different methods at various North America locations and from Japan appear at odds with the reported lack of seasonality in the European LF radio method [*Lastovicka et al.* 1993].

To understand the seasonal variations of the GWs, we need to know something about the GW sources. Most of the GWs in regions of relatively flat terrain, such as for South-East Michigan, are probably caused by strong convection, frontal systems, and the presence of the jet stream [e.g., *Eckermann and Vincent,* 1993].

We next discuss two possible causes for the strong observed seasonality. The first interpretation assumes that the seasonal variation of mesospheric GWs is an indirect manifestation of seasonal variation in the sources of the GWs at lower altitudes [*Garcia and Solomon*, 1985]. The second assumes that GWs may propagate to higher altitudes only in the summer and are filtered out by critical layers in other seasons. The two possible causes are not mutually exclusive and they can act together to generate strong seasonality.

The study by *Gedzelman* [1983] can shed some light on the first of these two possible causes/interpretations. *Gedzelman* [1983] found that short-period (~10 min) tropospheric GWs have larger amplitudes in winter, based on microbarograph data from Palisades, New York. Additionally, he also noted that GW amplitudes were correlated with the product of surface wind and temperature stratification between the surface and 700 mb. Recently, other lidar studies of stratospheric GWs [*Mitchell et al.*, 1991; *Murayama et al.*, 1994] have also found stronger low-altitude GWs in the winter season. *Mitchell et al.* [1991], for example, showed that maximum (minimum) GW energy density appeared in the winter (summer) in the 30-55 km altitude range at 52°N latitude. Their results showed that the ratio of the maximum to the minimum energy density decreases with altitude. The ratios were 6, 5, and 2.5 at altitudes 35, 45, and 55 km, respectively. This result seems to indicate that the stronger source of GWs in the winter does not necessarily mean stronger waves at high altitudes (above 80 km). To interpret their computational results, *Garcia and Solomon* [1985] suggested that GWs of greater amplitudes in the winter would break earlier at somewhat lower altitudes (~ 70 km) whereas those of weaker intensity would reach higher altitudes (above 80 km). Consequently, in this first interpretation, the seasonal variation at high altitudes becomes the opposite of that at lower altitudes.

As to the second possible interpretation for the observed GW seasonality, *Balsley et al.* [1983] plotted the range in the east-west direction of allowable phase velocities of tropospherically-generated GWs that propagate upward and *Ebel et al.* [1987] and *Taylor et al.* [1993] examined the wind field blocking diagram in the horizontal plane. All showed that the eastward (westward) propagating GWs would be filtered out in the winter (summer). The zonal wind profile has an eastward (westward) peak at 60 km altitude in winter (summer) near 40° latitude. The zonal wind profile also has a small eastward peak near 10 km altitude in both summer and winter and, on average, the surface wind direction is the same as that at 10 km. If the tropospherically-generated GWs are anisotropic, i.e., more eastward directed, then those GWs will be filtered out in the winter and pass through in the summer to higher altitudes, consistent with our results. The earlier study by *Ebel et al.* [1987] has shown that possibility. In their efforts to simulate the wind fluctuation orientation distribution, *Ebel et al.* [1987] had to assume a strong east-west anisotropy of the GW source on top of the neutral wind filtering effects in order for their simulated wind fluctuation orientation distribution to match the observational results. It should be pointed out, however, that they were not able to directly distinguish between the westward and eastward traveling waves. The fact that there is a close correlation between the surface wind and the short-period GW amplitude [*Gedzelman*, 1983], and the fact that the surface wind is, in general, eastward, are both consistent with this second possible interpretation.

Finally, we note that the large occurrence frequency of summer-time GWs observed over Peach Mountain could be an indication that more momentum (eastward) is transferred to the mesosphere in the summer at miod-latitudes. *Meek et al.* [1985] argued that eastward polarization of the GWs was required to balance the westward Coriolis torque and produce an eastward zonal wind shear above 85 km in the summer. *Nakamura* [1991] showed that the upward zonal momentum flux is stronger in summer than in the winter. These results are also consistent the observed tendency of PMO Gws to be eatward propagating in the summer.

4. Conclusions

We have studied the seasonal occurrence of GWs at a mid-latitude site (Peach Mountain Observatory, Michigan, 42.3°N; 83.7°W) using long-term, routine ASC OH nightglow observations. The observed GW occurrence frequencies (defined as OH relative brightness variations > ~7.5% for structures with characteristic spatial scales in the range 10's to 100's km) have a strong seasonal dependence. The occurrence frequency in the summer months reached ~70%, whereas in the spring, fall and the winter months (missing January) it was very low. Most GWs observed in the summer have a positive eastward propagating component. Supported by results of earlier studies [e.g., *Ebel et al.* 1987], we suggest that tropospherically-generated GWs may be anisotropic (eastward) thus propagating to the mesosphere only in the summer and being filtered out by the neutral wind during other seasons. It is also possible that the GWs can reach higher altitudes (above 80 km) without breaking due to smaller amplitudes at lower altitudes during the summer season. Further study is needed to differentiate between these hypotheses.

Acknowledgments. This work is supported by grants NSF ATM-9301867, ATM-9308157, ATM-9402289 to the University of Michigan from the National Science Foundation under the CEDAR program. The authors appreciate valuable discussions with Drs. C. A. Reddy, R. M. Johnson, A. G. Burns, and R. J. Niciejewski.

References

Broadfoot, A. L. and K. R. Kendall, The airglow spectrum, 3100-10,000Å, *J. Geophys. Res.*, *73*, 426-437, 1968.

Ebel, A., A. H. Manson, and C. E. Meek, Short period fluctuations of the horizontal wind measured in the upper middle atmosphere and possible relationships to internal GWs, *J. Atmos. Terr. Phys.* *49*, 385-401, 1987.

Eckermann, S. D. and R. A. Vincent, VHF radar observations of gravity-wave production by cold fronts over southern Australia, *J. Atmos. Sci.*, *50*, 785-806, 1993.

Fritts, D. C., J. R. Isler, and G. E. Thomas, Wave Breaking Signatures in noctilucent clouds, *Geophys. Res. Lett.*, *20*, 2039, 1993.

Garcia, R. R. and S. Solomon, The effect of breaking GWs on the dynamics and chemical composition of the mesosphere and lower thermosphere, *J. Geophys. Res.* *90*, 3850-3868, 1985.

Gedzelman, S. D., Short-period GWs: a study of their statistical properties and source mechanisms, *Mon. Wea. Rev.*, *111*, 1293-1299, 1983.

Lastovicka, J., J. Boska, and D. Buresova, Digital measurements of LF radio wave absorption in the lower ionosphere and inferred GW activity, *Ann. Geophysicae*, *11*, 937-946, 1993.

Llewellyn, E. J., B. H. Long, and B. H. Solheim, The quenching of OH* in the atmosphere, *Planet. Space Sci.*, *26*, 525-531, 1978.

Manson, A. H. and C. E. Meek, GW propagation characteristics (60-120 km) as determined by the Saskatoon MF radar (Gravnet) system: 1983-85 at 52° N, 107°W, *J. Atmos. Sci.*, *45*, 932-946, 1988.

Meek, C. E., I. M. Reid, and A. H. Manson, Observation of mesospheric wind velocities 2. cross section of power spectral density for 48-8 hours, 8-1 hours and 1 hour to 10 min over 60-110 km for 1981, *Radio Sci.*, *20*, 1383-1402, 1985.

Mende, S. B., R. H. Eather, and E. K. Aamodt, Instrment for the monochrmatic observation of all sky auroral images, *Applied Optics*, *16*, 1691, 1977.

Mitchell, N. J., L. Thomas, and A. K. P. Marsh, Lidar observations of long-period waves in the stratosphere, *Ann. Geophysicae*, *9*, 588-596, 1991.

Murayama, Y., T. Tsuda, and R. Wilson, H. Nakane, S. A. Hayashida, N. Sugimoto, I. Matsui, and Y. Sasano, GW activity in the upper stratosphere and lower mesosphere observed with the Rayleigh lidar at Tsukuba, Japan, *Geophys. Res. Lett.*, *21*, 1539-1542, 1994.

Nakamura, T., Mesosphere and lower thermosphere dynamics revealed by radar observations, Ph.D. Dissertation, 195pp, Kyoto University, 1991.

Senft, D. C. and C. S. Gardner, Seasonal variability of GW activity and spectra in the mesosphere region at Urbana, *J. Geophys. Res.*, *96*, 17,229-17,264, 1991.

Swenson, G. R. and S. B. Mende, OH emission and GWs (including a breaking wave) in all-sky imagery from Bear Lake, UT, *Geophys. Res. Lett.* *21*, 2239-2242, 1994.

Taylor, M. J., P. J. Espy, D. J. Baker, R. J. Sica, P. C. Neal, and W. R. Pendleton Jr., Simultaneously intensity, temperature and imaging measurements of short period wave structure in the OH nightglow emission, *Planet. Space Sci*, *39*, 1171-1188, 1991.

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

Q. Wu and T. L. Killeen, Space Physics Research Laboratory, Department of Atmospheric, Oceanic, and Space Sciences, 2455 Hayward, The University of Michigan, Ann Arbor, Mi 48109-2143. (e-mail qwu@engin.umich.edu; tkilleen@umich.edu)

(Received: March 24, 1995; revised: June 11,1996;
accepted: June 21, 1996)