Recent progress in mesospheric gravity wave studies using nightglow imaging systems

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This paper was prepared for presentation at the 9th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, 11-14 September 2005.

Abstract

During the past four decades a variety of optical remote sensing techniques have revealed a rich spectrum of wave activity in the upper atmosphere. Many of these perturbations, with periodicites ranging from ~5 min to several hours and horizontal scales of a few ten's of km to several thousands km, are due to freely propagating acoustic-gravity waves and forced tidal oscillations. Optical observations of the spatial and temporal characteristics of these waves in the mesosphere and lower thermosphere (MLT) region (~80-100 km) are facilitated by several naturally occurring, vertically distinct nightglow layers. This paper describes the use of state-of-the-art ground-based CCD imaging techniques to detect these waves in intensity and temperature. All-sky (180°) image measurements are used to illustrate the characteristics of small-scale, short period (< 1 hour) waves and to investigate their seasonal propagation and impact on the MLT region. These results will be contrasted with measurements of mesospheric temperature made using a separate imaging system capable of determining induced temperature amplitudes of much larger-scale wave motions and investigating night-to-night and seasonal variability in mesospheric temperature.

Introduction

Thermal tides and planetary waves dominate the motion fields in the MLT region (~80-100 km) due to their large horizontal and vertical amplitudes. However, current knowledge suggests that the largest systematic influence on the MLT region results from the much smaller-scale freely propagating gravity waves because of their ability to transport significant amounts of energy and momentum up from the lower atmosphere to the MLT region where they influence the mean wind and the larger-scale wave motions. As these short-period waves steepen due to adiabatic wave growth with altitude (or by reaching critical layers), they deposit their energy and momentum. In so doing they give rise to horizontal motions, which act to oppose the background flow and produce closure of the mesospheric jet (e.g. Holton, 1983; Garcia and Solomon, 1985), as well as vertical motions resulting in strong adiabatic cooling responsible for the unexpectedly cold summer mesopause at polar latitudes (as much as 90 K below the radiative equilibrium level). Thus, gravity waves, in particular small-scale waves (e.g. Fritts and Vincent, 1987) are now understood to be a key element in defining both the large-scale circulation, and the regional thermal structure and dynamical variability of the atmosphere at altitudes extending from the stratosphere into the MLT region.

To help quantify the effects of gravity waves at MLT heights their spatial and temporal characteristics, geographic distribution and seasonal variability are of key interest. However, as the mean winds and tides in the intervening atmosphere can modulate the gravity wave fluxes, and as they both vary strongly with latitude and season, the upward flux of waves (and hence momentum) at a given site and time is expected to vary significantly. Nevertheless, this variation in not yet known for any place on earth. Of equal importance is the investigation of the properties of the MLT region (background temperature and wind fields) in which the waves propagate and dissipate. Measurements using powerful Na wind-temperature lidar systems have provided unprecedented information on the vertical structuring of the MLT and the influence of tides on it (e.g. States and Gardner, 2000). However, due to their complexity lidar systems are usually operated only 2-3 nights/month. The resultant climatology therefore lacks necessary details associated with spring and fall transitions and short-term variability due to planetary waves, tides and gravity waves.

Image measurements of small-scale gravity waves

Images of the naturally occurring nightglow emissions afford an excellent method for investigating the horizontal morphology and dynamics of short-period (typically <1 hour) gravity waves. There are several prominent emissions at MLT heights which can be used for this study: the NIR OH bands (peak altitude ~87 km), the $O_2(0,1)$ Atmospheric band (~94 km), the OI(557.7 nm) green line (~96 km) and the Na D (589.2 nm) doublet (~90 km), all of which exhibit typical nighttime halfwidths (FWHM) of 8-10 km. As gravity waves propagate through these layers they induce significant modulation in the line-of-sight brightness and rotational temperature which is detected as radiance "structure". Several instruments have been developed to investigate the morphology and dynamics of the nightglow emissions. However, the exceptional capabilities of high quantum efficiency CCD arrays for low-light imaging studies at visible and NIR wavelengths makes them the detectors of choice for many gravity wave studies. In particular, all-sky (180°) imagers provide unique two-dimensional information on the spatial and the temporal properties of short-period gravity waves (~5-60 min) over a maximum (single site) area of ~500,000 km^2 [e.g. Taylor et al., 1995; Medeiros et al., 2003; 2004).

Figure 1 illustrates a short-period quasi-monochromatic wave event imaged near simultaneously in four different airglow emissions. The data were obtained from Bear Lake Observatory, Utah, USA, on 5 June 2002 and are typical of many of the extensive wave events detected from a number of sites at equatorial, mid and high latitudes. Imaging systems are most sensitive to relatively fast-moving waves exhibiting vertical wavelengths somewhat greater than the layer thickness (i.e. >8 km) and horizontal wavelengths (λ_h) ~5-200 km (i.e. significantly less than the maximum field of view). This is exactly the range of scale sizes that are the most important drivers of the MLT region dynamics. The majority of these waves (λ_h up to a few hundred km) are considered to be generated in the lower atmosphere by weather related disturbances such as convective activity, wind shear instabilities (jet streams), storms or fronts, or by orographic forcing (wind flow over mountainous regions). Image measurements of the airglow emissions can be made at any latitude and season providing a global, all year round capability. Such studies have revealed a wealth of small-scale wave activity from many sites around the world and it is not uncommon to observe several different wave patterns during the course of a night suggesting copious sources.

Gravity wave anisotropy

A common result arising from airglow image analysis is that the waves often exhibit marked preference in their propagation headings over a period of a few weeks. Such measurements made over the course of a year are quite rare but indicate strong anisotropy that varies systematically with the seasons. Taylor et al., 1993 were the first to investigate this anisotropy in image data and attributed it to wave blocking by winds. Their results, obtained over a 3-month period from Ft. Collins, Colorado, indicate that critical-layer filtering of the waves by the background winds in the intervening atmosphere (stratosphere and lower mesosphere) was an important factor in governing the propagation of wave energy into the MLT region. Critical layers occur when the horizontal wind vector along the direction of motion of the wave equals its observed horizontal phase speed [e.g. Tuan and Tadic, 1982). Under these conditions the intrinsic frequency of the gravity wave is Doppler-shifted to zero and its energy may be absorbed into the background flow.

Figure 2 shows the results of a 1-year investigation of all-sky OH wave data imaged from Cachoeira Paulista, Brazil (23°S) by Medeiros et al., 2003. The measurements have been divided into the four seasons with the observed directionality plotted as a function of the observed wave speed. (Note that the data have been divided into four months each for winter and summer and two months each for the spring and autumn transition periods.) It is clear that during the course of the year the direction of the waves switches over from eastward in the summer months to westward in the winter months.. This result is consistent with the reversal of the stratospheric winds, whose magnitudes are comparable to the wave phase speeds, and suggests that the small-scale gravity wave flux is being modulated strongly by the middle atmospheric winds. This situation is indicated by the shaded areas that represent height-integrated "blocking regions". These are forbidden regions for the waves resulting from wind filtering at lower altitudes and were constructed using CIRA-86 climatological wind profiles. The prevailing direction of the wave ensemble is clearly opposite to that of the height integrated blocking region. This said, other observers have also reported anisotropy in their wave measurements (e.g. Nakamura et al., 1999; Walterscheid et al., 1999; Hecht et al., 2001) suggestive of wave ducting rather than wind filtering. Ducting can occur due to shears in the background winds in the MLT region (termed Doppler ducting) or to changes during spring 1993 indicated that as much as 75% of the waves imaged over the mid-Pacific ocean exhibited ducted or evanescent characteristics (Isler et al., 1997). These results will be compared with new measurements from mid-latitudes that support a strong meridional reversal from summer to winter as well as the expected east-west reversal due to wind filtering.

Gravity wave and tidal temperature perturbations

A new type of imager termed a “Mesospheric Temperature Mapper” (MTM) was developed at Utah State University in the late 1990’s Like the all-sky camera systems this imager utilizes a high quantum efficiency (~50% at NIR wavelengths) bare CCD array. The large dynamic range and low noise characteristics (dark current ~0.1 el/pixel/sec at –50° C) of this array together with its high linearity and stability provide an exceptional capability for long-term, quantitative measurements of the nightglow emissions. The camera has a 90° field of view and is fitted with a fast (f/5.6) telecentric lens system permitting narrow-band (~1.2 nm) measurements of the OH Meinel (6,2) $P_1(2)$ and $P_1(4)$ rotational lines and two selected regions of the O_2 (0,1) Atmospheric band to investigate the mesospheric temperature and intensity perturbations at two distinct altitudes (~87 and ~94 km, respectively). Spatial resolution in the zenith is about 0.9 km which is quite sufficient to resolve even the shortest scale gravity waves (λ_h > 5km). In operation, sequential 60-sec exposures are made tow OH, two O_2 and as background sky measurement at 857 nm resulting in an effective sampling rate of ~6 min. Rotational temperatures are computed using the ratio method, described by Meriwether (1975) Comparisons of the MTM temperatures with those obtained by other well calibrated instruments (Na temperature lidars and FTIR spectrometers) indicate that our absolute temperatures are reliable to ± K. However, the precision of the OH and O_2 measurements (most important for determining wave perturbation amplitudes) is much higher at ~1-2 K.

The MTM has been used on several extended campaigns to investigate gravity wave and tidal harmonic characteristics and most recently to study the characteristics of the Semi-Annual Oscillation at low-latitudes. Fig 3 shows an example of a long period (~11-hr) oscillation and a superposed shorter period wave (~80 min) are evident in both the OH and O_2 emissions. The data were obtained from BLO on 2 December 2000. A marked phase shift exists between the two large amplitude waves with the O_2 signal leading the OH indicative of a downward progressing semidiurnal tide. The same signatures are evident in the respective band intensity data (not shown) which also yield information on the relative phase relationships between the intensity and temperature waves and their amplitudes. The ability to measure the temperature perturbations ($\Delta T/T$) as well as the intensity variations ($\Delta I/I$) induced by the passage of monochromatic gravity waves provides a new method for estimating their momentum flux, when combined with information on their intrinsic wave parameters (e.g. Swenson et al., 1999; Taylor et al., 2001).

Most recently MTM was moved to the U.S. Air Force Maui Optical Station (AMOS) on Haleakala Crater, Maui, Hawaii for long-term coordinated measurements as part of an instrument cluster, under the joint NSF/AFOSR (Air Force Office of Scientific Research) sponsored Maui-MALT initiative. Figure 4 illustrates this new capability which enables long-term, seasonal and inter-annual variability to be studied (e.g. Takahashi et al., 1995). This study is still in progress but has already yielded a significant amplitude Semi-Annual Oscillation in OH and O_2 temperatures (~5 K) at low latitudes (~20° N) and a marked asymmetry in the spring and autumnal amplitudes, suggestive of a significant annual component.

Summary

Image measurements of the nightglow emissions, which were once considered a novelty, have now proven to be an essential element in the quantitative investigation of gravity wave forcing of the MLT region. In particular their sensitivity to small-scale waves as well as their adaptability to multi-wavelength radiance and temperature measurements makes them a powerful tool for dynamical studies. The two-dimensional image data provide a direct measure of wave anisotropy, important for investigating wind filtering and ducting effects as well as novel data on wave breaking and turbulence leading to the transfer of momentum into the background flow. Ongoing observations as part of the Maui-MALT initiative are providing important new data on seasonal variability of mesospheric temperature as well as short-period gravity waves over the central Pacific Ocean where deep convective forcing is expected to be the dominant source mechanism for wave generation.

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Acknowledgements

We gratefully acknowledge the use of the US Air Force AMOS facility and the considerable help of R. Taft and S. AhYou (Boeing Corporation) with our long-term Maui-MALT measurements. Funding for the research performed by Utah State University was provided, in part, by the following grants from the National Science Foundation: ATM-9525815, -9813830, -0000959 and -0003218 for which we are most thankful.

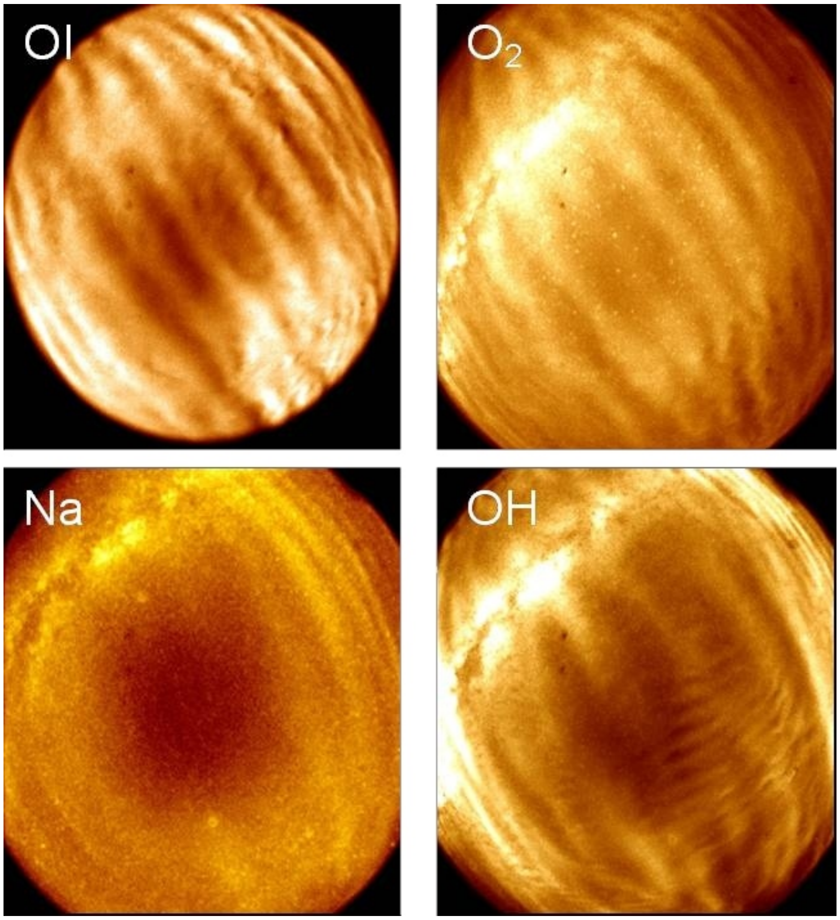

Figure 1 - Example of a spatially extensive short-period gravity wave event imaged near simultaneously in four nightglow emissions using an All-Sky (180°) bare CCD imager. The data were obtained from BLO on 5 June, 2002.

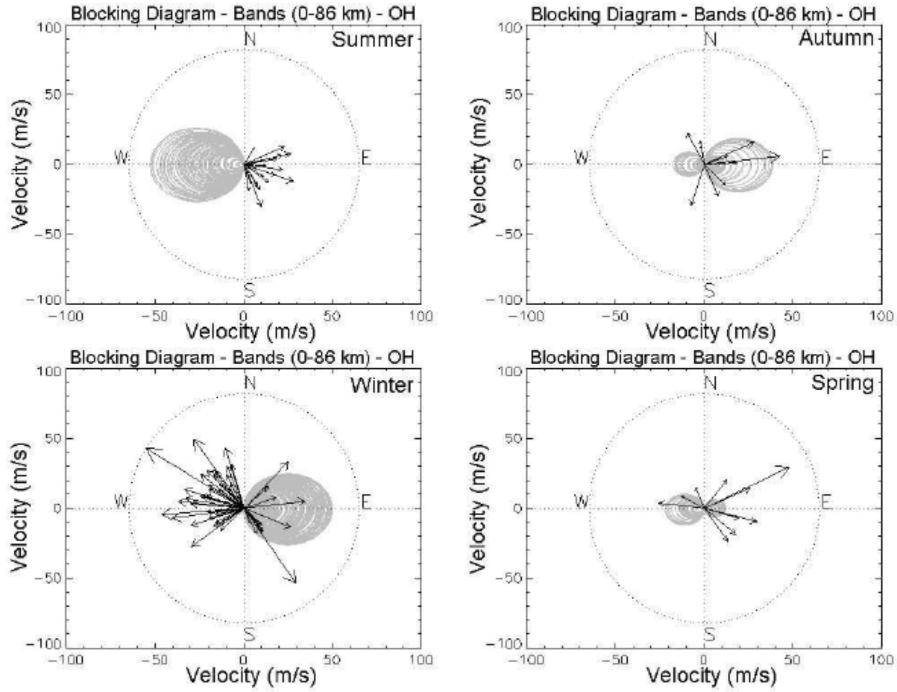

Figure 2 - Effect of seasonal variability on the propagation of short-period gravity waves observed from Cacheoira Paulista, Brazil (23°S, 45°W). The solid arrows show the magnitudes and directions of the horizontal phase speed of the waves imaged in the OH emission for each season. The shaded areas represent the expected blocked azimuth due to middle atmospheric wind filtering (Medeiros et al., 2003).

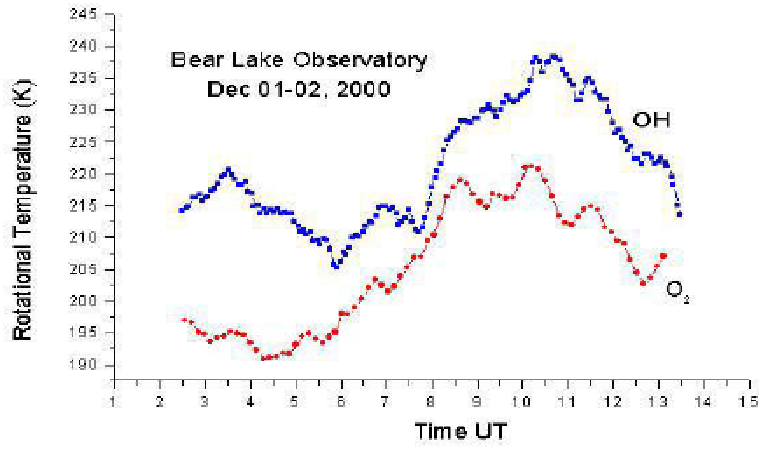

Figure 3 - Example MTM measurements of OH and O_2 rotational temperature both showing a large amplitude ~11- hr oscillation. The data were obtained from BLO on 2 December 2000. The two waves exhibit a marked phase shift with the O_2 leading the OH signal indicative of downward phase progression. A shorter period (~80-min) gravity wave is superimposed on both plots

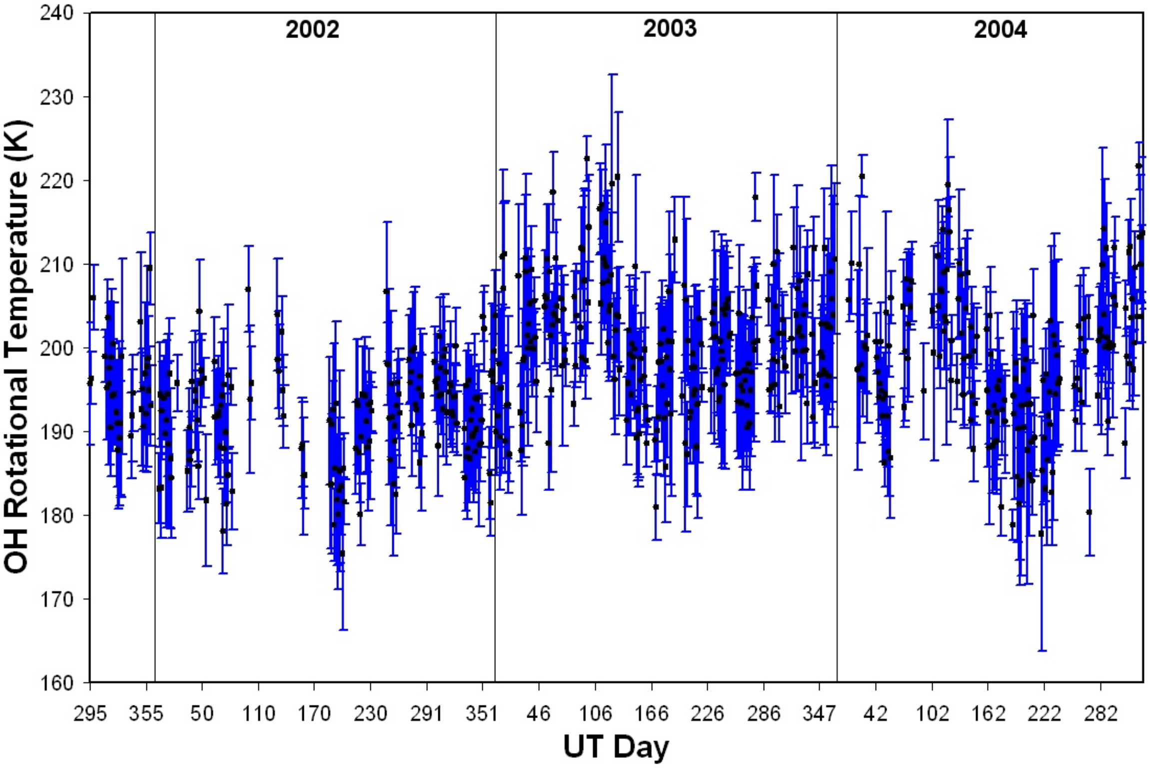

Figure 4 - Summary plot showing nightly mean OH rotational temperature as a function of UT day number for three consecutive years (2002-2004). The data were obtained by the MTM located at Maui, Hawaii as pert of the Maui-MALT program. (Note, the “error bars” indicate one standard deviation in nightly temperatures due primarily to geophysical variability).