

RECENT PROGRESS IN MESOSPHERIC GRAVITY WAVE STUDIES USING NIGHTGLOW IMAGING SYSTEMS

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ABSTRACT. A variety of optical remote sensing techniques have now revealed a rich spectrum of wave activity in the upper atmosphere. Many of these perturbations, with periodicities ranging from ~5 min to many hours and horizontal scales of a few tens of km to several thousands km, are due to freely propagating atmospheric gravity waves and forced tidal oscillations. Passive 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 momentum impact on the MLT region. These results are then contrasted with measurements of mesospheric temperature made using a new temperature mapping imaging system capable of determining induced temperature amplitudes of a large range of wave motions and investigating night-to-night and seasonal variability in mesospheric temperature.

Keywords: gravity waves, mesospheric dynamics, airglow imaging, seasonal variability.

RESUMO. O espectro de ondas na alta atmosfera tem sido revelado por uma variedade de técnicas de sensoriamento remoto ótico. Muitas destas perturbações apresentam períodos variando de 5 minutos a algumas horas e escalas horizontais que variam de dezenas a milhares de quilômetros e são devidas a livre propagação de ondas de gravidade e marés atmosféricas. Observações óticas das características espacial e temporal destas ondas na região (~80-100 km) da mesosfera e baixa termosfera (MLT) utilizam a variação da aeroluminescência atmosférica. Este trabalho descreve o *estado da arte* das técnicas que utilizam o imageamento via CCD para detectar estas ondas através das variações provocadas na intensidade e temperatura. Medidas de um imageador de céu todo (*All-sky*, 180°) são usadas para determinar as características de ondas de pequena escala e curto período (<1 hora) e investigar a sazonalidade da direção propagação destas ondas, como também o depósito de momento na região da MLT. Estes resultados são comparados com medidas da temperatura atmosférica realizadas usando um novo sistema de imageamento de mapeamento da temperatura mesosférica capaz de determinar variações nas amplitudes da temperatura provocadas pelas ondas de gravidade através da investigação da variabilidade noturna da temperatura mesosférica.

Palavras-chave: ondas de gravidade, dinâmica da mesosfera, luminescência atmosférica, sazonalidade, imageador, oscilações atmosféricas.

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INTRODUCTION

It is now known that the largest systematic influence on the mesosphere and lower thermosphere (MLT) region (altitude range ~ 80 – 100 km) results from relatively small-scale freely propagating gravity waves. This is because of their ability to transport significant amounts of energy and momentum up from the lower atmosphere source regions to the MLT region where they strongly influence the mean wind and the larger-scale tidal 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 mainly in the MLT region. 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 & 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, short period waves (e.g. Fritts & 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.

Knowledge of the spatial and temporal characteristics, geographic distribution and seasonal variability of these waves at MLT heights is therefore 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 momentum at a given site and time is expected to vary significantly. Optical remote sensing measurements have established the global presence of these waves at equatorial mid- and high-latitudes and their basic properties. However, their momentum coupling and effects on the MLT region have only been investigated from a limited number of sites, and their seasonal variability are not well known for any place on earth.

Of equal importance to this investigation is accurate knowledge of the basic properties of the MLT region (background temperature and wind fields) in which these waves propagate and dissipate. Measurements using meteor radar and more recently powerful Na lidar systems have provided unprecedented information on the vertical structuring of the MLT and the influence of tides. In particular, Na wind-temperature lidar systems provide high-resolution, height-resolved measurements of the wind and temperature field over the range ~ 80 – 100 km (e.g. States & Gardner, 2000) essential for investigating the effects of tides and

gravity waves on the MLT region. However, due to their complexity lidar systems are usually operated only 2–3 nights/month and climatology studies, therefore, lack necessary details associated with spring and fall transitions and shorter term variability due to planetary waves, tides and gravity waves.

Long-term optical measurements can provide important information, not only on the properties of the gravity waves but also in the background wind and temperature field. Here we present some recent results on gravity wave seasonal anisotropy obtained using all-sky (ASI) monochromatic imagers and novel measurements of seasonal temperature variability in the MLT at low-latitudes using the CEDAR Mesospheric Temperature Mapper (MTM). As we will show, imagers are becoming powerful tools for remote-sensing studies of the upper atmospheric dynamics as they provide key data complementary to those usually obtained using established radar and other passive and active optical techniques. In particular, imagers are relatively low cost and can be run automatically for extended periods (years) essential for long-term investigations of the MLT climatology.

IMAGE MEASUREMENTS OF SHORT-PERIOD 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 near infra-red (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 night-time half-widths (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 $\sim 500,000$ km² (e.g. Taylor et al., 1995; Medeiros et al., 2003; 2004).

Figure 1 is a photograph of a Utah State University (USU) all-sky imager (originally developed in 1993), mounted in a frame



Figure 1 – All-sky, monochromatic CCD imager developed at Utah State University for imaging short-period gravity waves in the faint MLT emissions. The camera system is mounted vertically to view the night sky through a perspex dome.

under a perspex dome. A high-resolution 1024×1024 pixel, back-thinned CCD array is used providing excellent, low-noise measurements of the airglow emissions. The CCD is cooled to -40°C to limit the dark current to typically a few electrons/pixel/sec and a telecentric lens arrangement coupled to a 6-position filter wheel is used to provide wide-field (180°) sequential images of selected airglow emissions (filter bandwidths < 2 nm). Typical exposure time range from 15 sec for the bright NIR OH bands to 90 sec for the OI(557.7 nm) line emissions. This instrument is a compact, well-proven field system capable of autonomous operation, long-term operation with remote control and data access via the internet.

Figure 2 illustrates a short-period quasi-monochromatic wave event imaged near simultaneously in four different MLT airglow emissions (OI, O₂, Na and OH). The data were obtained from Bear Lake Observatory (BLO), Utah, USA on 5 June 2002 and are typical of many of the spatially extensive, but short-period wave events detected from a number of sites at equatorial, mid- and high latitudes. In this example the stars have been removed, prior to spectral analysis to determine the horizontal wavelength ($\lambda_h = 45$ km) and motion ($v_h = 45\text{m/s}$) of the waves pattern (observed period 15 min). Note, the Milky Way is still evident as a bright band in the upper left of each image. Also note the presence of a set of much smaller-scale ripple waves in the lower-altitude

(~87 km) OH emission. These are mainly due to spatially localized shear or convective instabilities and unlike the gravity waves are generated in-situ (e.g. Taylor & Hapgood, 1990; Hecht, 2004 and references therein).

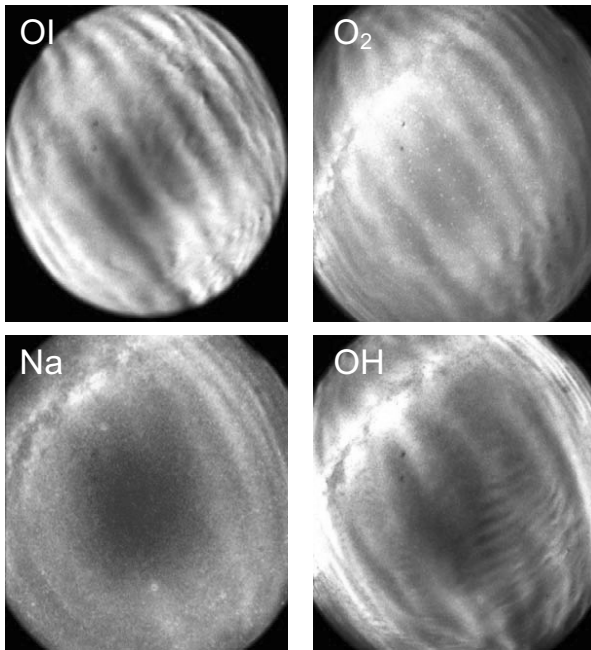


Figure 2 – Example of a spatially extensive short-period gravity wave event imaged near simultaneously in four nightglow emissions using an all-sky (180°) bare CCD imager. The data were obtained from BLO on 5 June, 2002. (Note: stars have been removed from these data to aid spectral analysis.)

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

An important result arising from airglow image analysis is that short-period waves often exhibit marked preference in their pro-

pagation headings when observed over intervals of a few weeks. Such measurements made over the course of a year are still quite rare but they all indicate strong anisotropy that also appears to vary 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, indicated 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 (and momentum) 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 & 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 3 shows the results of a 1-year investigation of OH wave data imaged using the USU all-sky imager sited at Cachoeira Paulista, Brazil (23°S) (Medeiros et al., 2003). This figure compares measurements of the wave velocities observed during the summer and winter seasons (four months each). Note, only sparse data were obtained during the equinox periods and are not shown here. Each plot shows the horizontal direction of motion of quasi-monochromatic waves versus their observed wave speed. It is clear that during the course of the year the dominant direction of the waves switches over from eastward in the summer months to mainly 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, at least at low-latitudes, the small-scale gravity wave flux is being modulated strongly by the middle atmospheric wind field. 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.

For comparison, Figure 4 shows the results of a similar wave analysis performed on two seasonal data sets obtained at Ft. Collins, Colorado (40°N) and at BLO, Utah (41.6°). These sites are at similar latitudes but separated in longitude by ~550 km. In each of these figures the data have been summed into 15° wide sectors and plotted versus number of events. The Ft. Collins data were obtained in 1997–1998 and show a marked meridional anisotropy with strong motions towards the north during summer and a switch over to a bimodal-like distribution during the win-

ter months exhibiting strong southward motion, but also significant north-westward motion. These data also show a more subtle, but never the less a distinct zonal switch over from an eastward component of wave propagation during the summer months to a distinct westward component of wave propagation during winter, which is consistent with critical-layer blocking effects. However, the dominance of the meridional signature is unexpected. The BLO data were recorded during 2002 and 2003 and show remarkable similarities to the Ft. Collins data for both the summer and winter seasons with dominant northward (poleward) motion during the summer and bimodal propagation during the winter months. (Note the change of scale in Figure 4d due to reduced number of events observed during the wintertime at BLO.) As these two data sets were taken from similarly located sites but separated in time by ~ 5 years they clearly show that this reversal is a recurrent seasonal effect (at least at mid-latitudes).

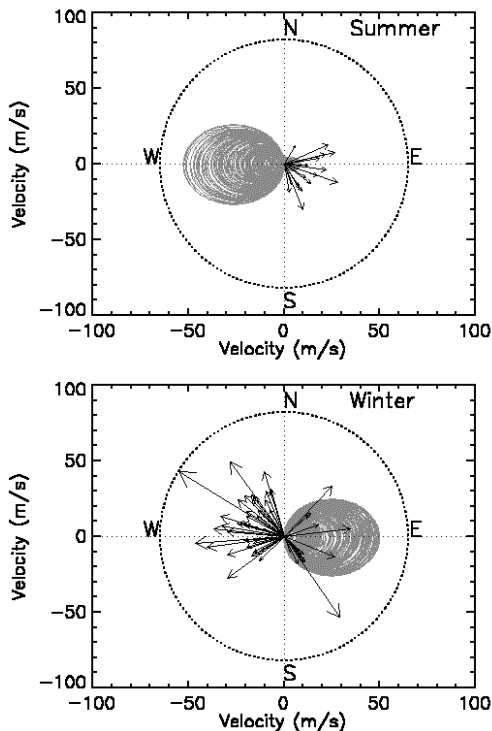


Figure 3 – Effect of seasonal variability on the propagation of short-period gravity waves observed from Cachoeira Paulista, Brazil (23°S , 45°W). The solid arrows show the magnitudes and directions of the horizontal phase speed of the waves imaged in the OH emission for summer and winter seasons. The shaded areas represent the expected blocked directions for wave propagation during these two seasons (due to background wind-filtering effects). Adapted from Medeiros et al. (2003).

Other observers have also reported anisotropy in their wave measurements (e.g. Nakamura et al., 1999; Walterscheid et al., 1999; Hecht et al., 2001), some with strong meridional aniso-

tropy. Walterscheid et al. (1999) suggested this could be due to wave ducting rather than wind filtering effects. Ducting can occur due to shears in the background winds in the MLT region (termed Doppler ducting) or to changes in the local temperature gradient (termed thermal or Brunt ducting). Due to their relatively small scale sizes, short-period waves are susceptible to both thermal and Doppler ducting in the vicinity of the mesopause (e.g. Chimonas & Hines, 1986). Unlike freely propagating waves, ducted waves can travel large horizontal distances from their source regions and their impact on the MLT remains uncertain at this time. For example, an analysis of image data obtained from Hawaii during spring 1993 indicates that as much as 75% of the waves imaged over the mid-Pacific ocean exhibited ducted or evanescent characteristics (Isler et al., 1997). However, a recent study by Nielsen et al. (2006) suggests mainly freely propagating waves at high-latitudes during the winter months. Clearly further seasonal investigations of the nature (i.e. freely propagating or ducted) of short-period wave and their directional anisotropy are important.

GRAVITY WAVE AND TIDAL TEMPERATURE PERTURBATIONS

A new type of imager termed a “Mesospheric Temperature Mapper” (MTM) was developed at USU in the late 1990s. Like the all-sky camera systems this imager utilizes a high quantum efficiency ($\sim 50\%$ at NIR wavelengths) bare CCD array. The large dynamic range and low noise characteristics (dark current ~ 0.1 electrons/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 $\text{O}_2(0,1)$ 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 ($\lambda_n > 5$ km). In operation, sequential 60-sec exposures are made: two OH, two O_2 and a 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 Fourier Transform Infra-red spectrometers) indicate that our absolute temperatures are reliable to ± 5 K. However, the precision

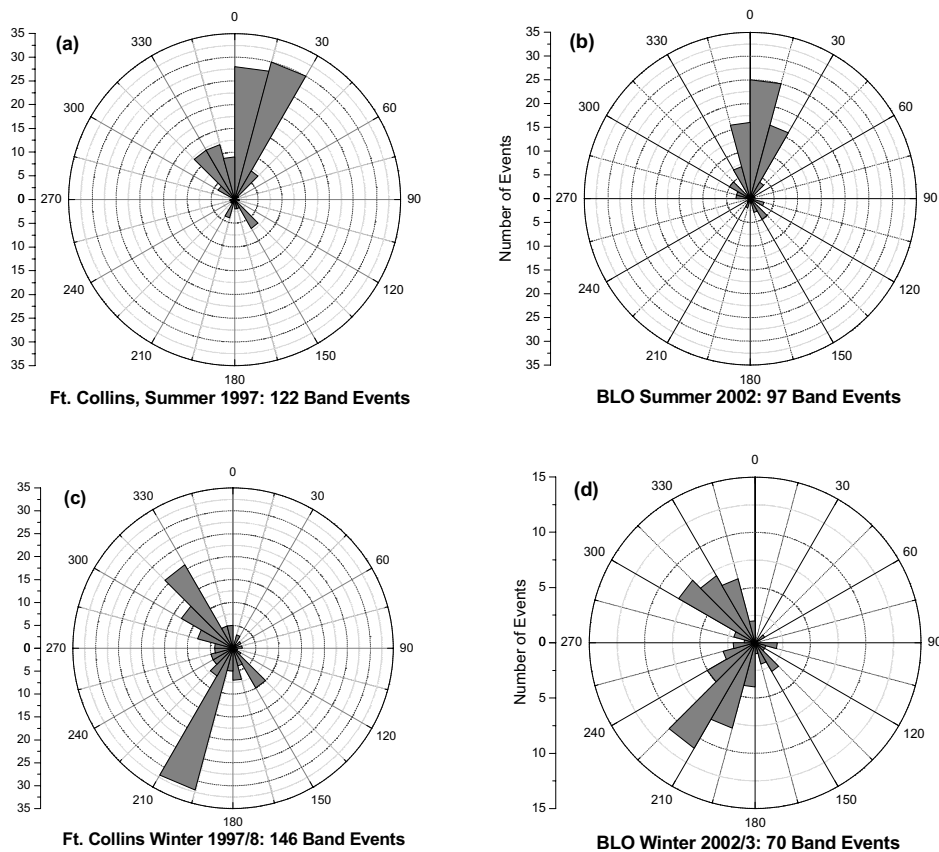


Figure 4 – Seasonal summer-winter comparison of short-period gravity wave anisotropy observed at Ft. Collins (1998) and BLO (2002-2003), two well separated but similar latitude sites in the USA. Both data sets are remarkably similar and exhibit strong meridional anisotropy, with a marked preference for northward wave motion during the summer months switching over to a bimodal-like distribution with strong southward wave motion. (Note the change of scale in Figure 4d.)

of the OH and O₂ measurements (most important for determining wave perturbation amplitudes) is much higher at ~1-2 K (Zhao et al., 2005).

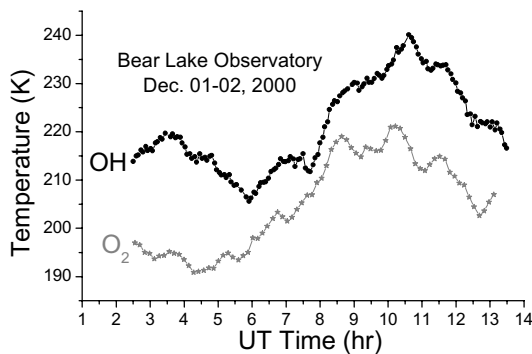


Figure 5 – Example MTM measurements of OH and O₂ temperature showing a large amplitude tidal oscillation of period ~11 hours with superposed smaller-scale gravity wave of ~80 min period. The data were obtained from BLO on 1/2 December 2000 and show a marked phase shift with O₂ leading signal indicative of a downward progressing tide.

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 (SAO) at low-latitudes. Figure 5 shows an example of a long period (~11 hr) oscillation and a superimposed shorter period wave (~80 min) evident in both the OH and O₂ emissions. The data were obtained from BLO on 2 December 2000. A marked phase shift (~1 hour) exists between the two large amplitude waves with the O₂ signal clearly leading the OH oscillation 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

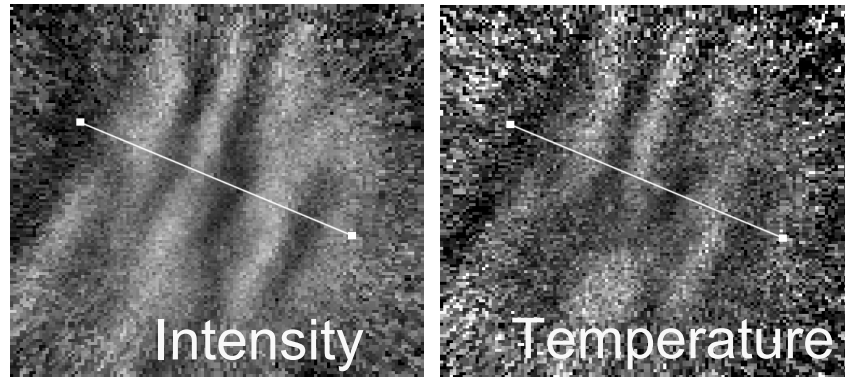


Figure 6 – Maps of OH (6, 2) band intensity and rotational temperature derived from MTM data obtained on 11 April, 2002. The observed period of the gravity wave was 17 min. The lines marks location of intensity and temperature scans shown in Figure 7.

their intrinsic wave parameters (e.g. Swenson et al., 1999; Taylor et al., 2001).

This technique is illustrated in Figure 6 which shows maps of intensity and OH rotational temperature derived from the MTM. The data were obtained from the summit of Haleakala Crater, Maui, Hawaii as part of the Maui-MALT program. The figures show a short observed period gravity wave imaged on 11 April, 2002 ($\lambda_h = 37$ km, $v_h = 36$ m/s, observed period of 17 min). The black lines in each case show the location of intensity and temperature scans used to determine the amplitude and phase of the wave in each case (see Fig. 7). Simultaneous wind measurements (not shown) have been used to determine the intrinsic wave period and to show that this wave was freely propagating (using the “vertical wave number squared” method described by Isler et al., 1997). Using these data an estimate of the horizontal momentum flux of this quasi-monochromatic wave can be obtained using the method described in Liu & Swenson (2003). Using an estimated Brunt-Vaisala period of 5 min (derived from simultaneous Na lidar temperature data), the magnitude of the momentum flux was found to be 30 ± 10 m²/s². This is consistent with previous (limited) measurements using lidar and optical/image methods (e.g. Gardner et al., 1999; Swenson et al., 1999) for a relatively low-contrast wave event but well below that determined by Fritts et al. (2002) for a high-contrast wave breaking event reported by Yamada et al., 2001. This example illustrates the capability of the MTM when combined with simultaneous Na lidar data for accurate momentum flux measurements.

For the past four years the MTM has operated near-continuously from the U.S. Air Force Maui Optical Station (AMOS) on Haleakala Crater, Maui, Hawaii. Our primary goal has been to obtain long-term coordinated measurements using a cluster of

instruments including and Na wind-temperature lidar, a meteor wind radar and other passive optical measurements. These data were obtained as part of a joint NSF/AFOSR (Air Force Office of Scientific Research) sponsored Maui-MALT initiative. Figure 8 illustrates this new capability of the MTM for long-term, seasonal and inter-annual variability studies (Taylor et al., 2005). The figure shows three consecutive years of data from 2002 to 2004 inclusive. The “error bars” represent the standard deviation on the nocturnal temperature variability for each night due mainly to geophysical variability (tides).

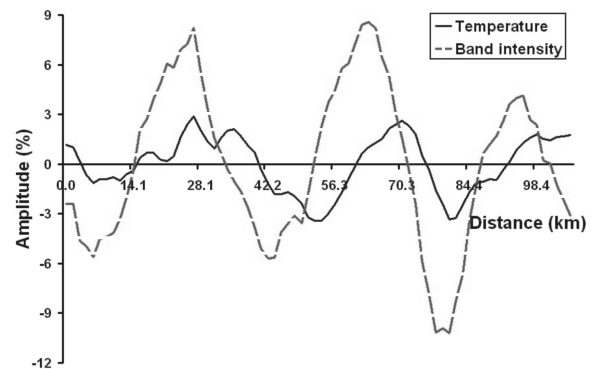


Figure 7 – Plot of relative band intensity and rotational temperature perturbation amplitudes for the data of Figure 6.

Previous airglow measurements at equatorial and low-latitudes from Brazil have shown the presence of a strong SAO in emission intensity and temperature (Takahashi et al., 1995). Our data recorded at low-latitudes ($\sim 20^\circ$ N) show evidence of an SAO and possibly an annual oscillation (AO) in OH temperature (and O₂ temperature, not shown here). This is illustrated by the solid curve in Figure 8 which shows a least-squares-fit assuming

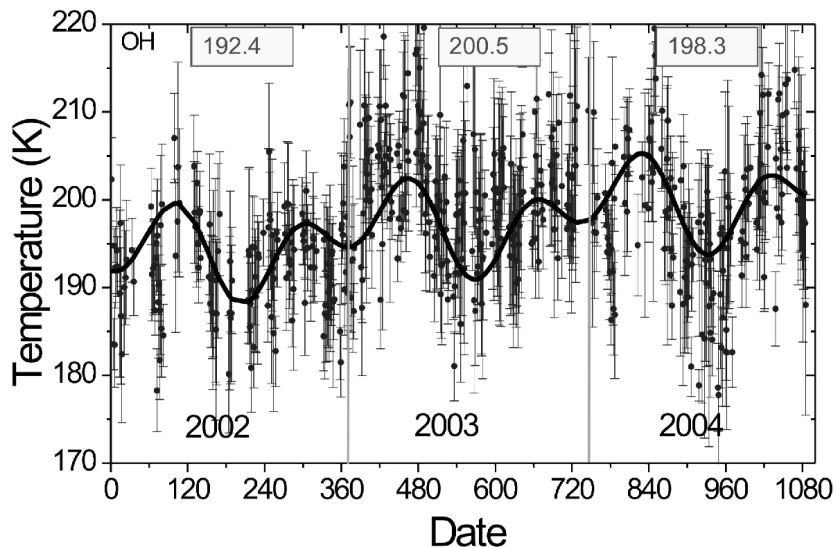


Figure 8 – Plot of nightly averaged OH rotational temperatures for three consecutive years 2002-2004. (Note, only data >4 hours in duration are shown). The data show evidence of a semi-annual oscillation as well as an annual oscillation as expected from this low-latitude site but rarely measured to date.

a mean, AO and an SAO oscillation. The amplitude of each component is similar at ~ 3.5 K. This study is still in progress but has already yielded a significant amplitude SAO in OH and O₂ temperatures consistent with the southern hemisphere observations by Takahashi et al. (1995). The marked asymmetry in the spring and autumnal amplitudes was not evident in the equatorial data of Takahashi et al. (1995) but is most suggestive of a significant annual component. The high “density” of the data points illustrates well the capability of the MTM for long-term measurements.

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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