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HIGH FREQUENCY ATMOSPHERIC GRAVITY WAVE DAMPING IN THE MESOSPHERE

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ABSTRACT

Correlative measurements of temperature and winds by Na lidar and brightness in OH and O₂ Atmospheric band airglow have been made at Albuquerque, NM and Maui, HI for a study of high frequency (period less than 30 minutes) Atmospheric Gravity Waves. Wave studies from four nights have been made and the correlative information describes the intrinsic wave properties with altitude, their damping characteristics, and resulting accelerations to the large scale circulation in the 85-100 km altitude region. Generally, saturated to super-saturated conditions were observed below 95 km. Above this altitude, they were less saturated to freely propagating.

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BACKGROUND AND AGW POTENTIAL ENERGY

Atmospheric Gravity Waves (AGWs) are small scale dynamic features which propagate into the upper mesosphere and lower thermosphere. Their origin is primarily the lower atmosphere. The waves which reach the upper mesosphere carry a significant flux of horizontal momentum. These waves dissipate and exchange momentum with the mean flow [Fritts, D. C. and T. E. van Zandt, 1993]. The effects on the middle atmosphere circulation are significant, resulting in a residual circulation in the 80-120 km altitude region [e.g. Hamilton, 1996 and McLandress, 1998]. It is the high frequency waves that carry a large fraction of the momentum [e.g. Vincent, 1984].

The vertical fluxes of AGW energy (F_E) and momentum (F_M) are related to the intrinsic parameters of the wave as described in equation 1 and 2 below [Vincent, 1984], i.e.

$$F_E = \frac{-\rho_0 \lambda_z^2}{\lambda_x \tau_{BV}} \frac{g^2}{N^2} \left\langle \left(\frac{T'}{T} \right)^2 \right\rangle \quad (1)$$

and

$$F_M = \frac{m}{\rho_0 \omega} F_E \quad (2)$$

where ρ - atmospheric density, T - temperature, T' - wave induced temperature change, g - gravitational acceleration, N - Brunt Vaisala frequency, λ_x - horizontal wavelength, λ_z - vertical wavelength, m - vertical wave number, τ_{BV} - Brunt Vaisala period, and ω - wave frequency. The relationship of the wave amplitude, I' , to the intensity of the OH airglow is described by Swenson and Liu [1998], i.e. $T'/T = CF \cdot I'/I$, where CF - Cancellation Factor, and I and I' - OH airglow intensity, and wave perturbed intensity change, respectively. It is the wave potential energy (F_P), i.e.

$$F_P = \frac{g^2}{2 \cdot N^2} \left\langle \left(\frac{T'}{T} \right)^2 \right\rangle \quad (3)$$

which is important to characterize with altitude in order to establish the degree of damping. Inspection of (1) suggests that for a wave with fixed intrinsic parameters, the waves' perturbation amplitude factor would necessarily increase to compensate for decreasing atmospheric density, for a condition where the wave was undamped, i.e. F_E being constant with altitude. Assuming the atmospheric scale height (e-fold) of 6 km, this undamped wave condition is met for wave amplitude increases, e-folding in 12 km. A 'saturated' condition is one where the wave amplitude is constant with altitude. It is these expressions which are used to calculate the wave energy and momentum for the studies described here. It is noted from equation (3) that the wave potential energy is proportional to the square of wave perturbation amplitude and inversely to N^2 , the convective stability parameter, i.e.

$$N^2 = \frac{g}{T} \left(\frac{dT}{dz} + \frac{g}{C_p} \right). \quad (4)$$

The high frequency waves are those with large vertical wavelengths and small horizontal wavelengths. Note in equation (1) that for a given wave amplitude (T'/T), the vertical flux of the wave energy is proportional to λ_z^2/λ_x . Waves with periods <30 minutes have intrinsic phase speeds typically >40 m/s, $\lambda_z > 10$ km, $20 < \lambda_x < 100$ km and fall into this class of waves. These are a class observed in airglow emission layers. If these waves are being damped, the accelerations they impose on the mesospheric wind fields exceed by a large factor, contributions made from other parts of the AGW spectrum, in this altitude region as was deduced from a detailed study of waves with lidar, airglow and rocket measurements during the TOMEX campaign, October 26, 1999 [Li *et al.* 2002b]. The real challenge is to deduce the degree of damping in the upper mesosphere. Are they propagating through the region causing little or no effect, or is wave damping evident?

INTRINSIC WAVE PARAMETERS

Observations of the atmosphere in the upper mesospheric region (80-110 km) have been made with correlative measurements from Na lidar and airglow instrumentation at Albuquerque, NM (1998-2000) and Maui, HI (2001-2002). Gardner *et al.* [1998] and Haque and Swenson, [1999] describe the lidar and optical imager capabilities used in this analysis, respectively. Correlative measurements from these instruments have been analyzed for four nights (two at Albuquerque, NM, and two at Maui) where the temporal and spatial sampling with the Na lidar is analyzed for the high frequency wave amplitudes. The combination of the measurements and the dispersion relationship, i.e.

$$m^2 = \frac{(N^2 - \omega^2)}{(\omega^2 - f^2)} k^2 + \frac{\omega^2}{gH} - \frac{1}{4H^2}, \quad (5)$$

provide the necessary information to deduce the AGW intrinsic parameters. In (5), f – inertial frequency and H – scale height. This data is combined to resolve the intrinsic wave parameters as well as amplitude and relevant atmospheric information necessary to deduce the wave potential energy with altitude. For two of these nights, the accelerations induced in the process of wave damping are calculated. Altitude domains of 3-5 km are found to have large accelerations (100's $\text{m s}^{-1}/\text{day}$) for waves which persisted throughout the night from fixed directions, characteristic of the most often observed 'wave trains' evident from structure observed in OH airglow imagers, for example.

The observations are combined to give λ_x from allsky OH airglow images at an assumed centroid height of 86 km [Swenson and Gardner, 1998]. λ_z is deduced from observed phase speeds of the high frequency waves observed in the OH imager, and Doppler corrected for winds measured by the Na wind/temperature lidar as described by Swenson *et al.* [2000]. N^2 was calculated using expression (4) above and temperatures measured by the lidar between 80 and 105 km [Gardner *et al.*, 2002; Zhao *et al.*, 2002]. With the information described, the wave intrinsic parameters are calculated for the 86 km altitude except for the wave amplitude.

Wave amplitudes for this study were measured by the Na wind/temperature by operating a unique operational mode. The telescope was pointed in the zenith for the specific purpose of measuring high temporal resolution sampling of temperature and vertical velocity from the zenith volume with a 60 sec integration time. Once each hour, on the hour, the normal azimuthal mode of pointing through the cardinal directions for the recovery of horizontal winds was accomplished (~ 10 minute cycle). The four nights of data used in this study include two nights, Oct 26, 1999 (TOMEX) and Dec 7, 2000 from Albuquerque, NM, and two nights, April 9 and July 14,

2002, from Maui, HI. On April 9, 2002, the azimuth scans to measure winds were not performed. An exception in operation was Oct. 26, (TOMEX) night where a series of measurements were made at a large slant path to the south of Albuquerque over the White Sands Missile Range. The wave amplitudes from that night were deduced from lidar when it was panned in elevation scans and the T and T' were deduced from the time histories of the vertical pan data at a fixed azimuth angle, as described by Li et al., [2002].

DATA

Data is presented in each of the four nights in an evolution of geophysical description. Examples of intrinsic elements and damping characteristics are shown for the given nights.

April 9, 2002 (Maui)

Fig. 1. One column from the center section of each allsky OH image is concatenated to form a single image for both North-South (top) and East-West (bottom) for April 9, 2002, at Maui, HI

Allsky image sequences are summarized in 'keograms', as illustrated and defined in the caption of Figure 1. This is very typical of a high frequency persistence for a given nights observations as has often been described by Taylor et al. [1993] and Tang et al. [2002] for example. High frequency persistent wave trains frequently persist from a given direction through the observable night, for example. In the N-S keogram, the waves initially appear on the northern horizon and later disappear off the southern horizon, indicative of a southward meridional component in the wave, a trend which persisted for the night. Similarly, note in the East-West keogram the zonal component is eastward.

Figure 2 illustrates wave temperature time histories (left) and power spectra (right) for the 6-9 UT on April 9. The time histories of temperature are calculated for every 2 km altitude increment with 5 km altitude integrations of lidar data about each altitude increment. The vertical wavelengths for the fast waves at Albuquerque were found to be 26 km with a standard deviation of 9 km [Swenson et al., 2000]. Inspection of layer structures of lidar temperatures in figure 2 (left) suggest the vertical wavelength of these structures are large, consistent with that deduced from phase speed and the dispersion relationship. Airglow layer thicknesses are insensitive to vertical wavelengths < 12 km [Swenson and Gardner, 1998]. Altitude integration of lidar binned samples of 5 km is geophysically justified based on the large vertical wavelength characteristic of the 'fast', high frequency waves. The wave number power spectrum for the lidar data which has been filtered

for the high frequencies is noted to significantly reduce in amplitude between 83 and 89 km, and increase again above 95 km, indicative of possible damping. N^2 is plotted in Figure 3. On this night, the stability increased to a maximum near 88 km, decreased to 93 km and was relatively constant above. The decrease in amplitude occurred in the same altitude region as N^2 decreased. The effects of the stability are most noted on the effects it has on the vertical wavelength (or wave number, m) as constrained by the dispersion relationship (equation 5), an example of which is shown later for the July 14 data. The wave parameters for this night are tabulated in Table 1, along with the average parameters for all nights described in this study.

July 14, 2002 (Maui)

The combined intrinsic parameters for the data acquired on July 14, 2002 at Maui were used to calculate the vertical flux of horizontal momentum and the accelerations associated with the divergence in the momentum flux with altitude. These are shown in Figure 4. The expression for the momentum flux is equation (1). Note that the vertical flux of horizontal momentum decreased from $\sim 11 \text{ m}^2\text{s}^{-2}$ to $\sim 10\text{-}20\%$ of that value at 90 km in both the meridional and zonal components. The accelerations shown on the left are largest at the bottom of the layer and become negligible above 90 km.

Fig. 2. (Left) An example of temperature measurements made by Na lidar, with 5 km vertically integrated altitude bins, centered at altitudes indicated between 85 and 99 km, in 2 km increments, for April 9, 2002. The vertical bar in the upper right indicates 10°C. (Right). Spectral power vs. wave number for periods of 6-30 minutes for each of the altitudes shown at the right. The power plots shown are for the entire nights data taken April 9, 2002.

Fig. 3. A plot of nightly averaged N^2 vs. altitude for April 9, 2002

Table 1. Wave Parameters

Date	1999-12-07	2000-10-26	2002-04-09	2002-07-14
Site	Albuquerque	Albuquerque	Maui	Maui
Observed Period (min)	7.7	13.2	12.4	7.5
Intrinsic Period (min)	7.0	15.0		7.7
Horizontal Wavelength (km)	26.0	63.0	31.6	25.2
Vertical Wavelength (km)	35.5	43.0		21.3
Observed Phase Speed (m/s)	59.2	81.0	42.5	56.0
Intrinsic Phase Speed (m/s)	63.2	71.0		55.0
Amplitude (% of T'/T_0)	0.56	0.81	1.9	1.2

On this night, with a persistent wave flux from the high frequency waves, we can calculate the approximate wave-wave coupling to the diurnal tide for example. The diurnal tide downward propagates ~ 1 km per hour. Given this wave was persistent for a large portion of the night, the phase of the tide extending from 90 to 85 km

would have experienced an acceleration of 50 m/s by the time (5 hours) the tidal phase reached 85 km compared to near 0 m/s acceleration at 90. For the acceleration profile shown in Figure 4, this would constitute a near linear velocity gradient between 85 km (50 m/s) and 90 km (0 m/s).

Fig. 4. (Left) Momentum flux vs. altitude calculated for a high frequency, monochromatic wave persistent on July 14, 2002. The T' for the momentum flux was determined from the lidar measured T' , an example of which is shown in Figure 2. (Right) Accelerations imposed on the mean flow for the gradient in the momentum flux shown on the left.

October 26, 1999 (TOMEX), Albuquerque

The accelerations for a wave from the NW-SE persisted on this night during the TOMEX rocket campaign. Details of the wave field are described in Li et al. [2002] and the referenced papers. The accelerations by this wave are shown in Figure 5, in similar scales to those shown in Figure 4. Note that on this night the accelerations were much higher in altitude and of similar magnitude. Again, a significant issue for consideration is the fact that this wave train persisted from the same direction for most of the night.

Fig. 5. Same as Figure 4 except for October 26, 1999 at Albuquerque. Note the magnitudes of the accelerations are similar to those described in Figure 4 but the altitudes of maximum accelerations are much higher in altitude.

The N^2 time histories are color coded and plotted in Figure 6. Note that the altitude of maximum instability ~ 90 km coincides with the altitude of maximum AGW acceleration as indicated in Figure 5. Association of maximum wave damping with instability has been suggested by Li et al. [2002]. This is clearly an issue for further study. The study should also include the issue of shear instabilities and its relationship to the degree of damping associated with the high frequency AGWs.

Fig. 6. N^2 vs. altitude for October 26.

December 7, 1999 (Albuquerque)

A fourth night investigated was December 7, 1999, at Albuquerque. The intrinsic properties of the waves were characterized every 2-3 hours and the effective wave amplitude versus altitude was calculated for each of the time increments when the wave characteristics were relatively constant.

Fig. 7. Plots of T'/T as measured by the Na lidar, vs. altitude. The lines plotted for undamped and damped waves assume N^2 is constant. On this night, wave conditions were studied for the varied amplitude and intrinsic parameters deduced.

at this time.

Figure 7 is a plot of the normalized wave amplitudes (T'/T) normalized to the amplitude at 82.5 km. The plots on the left in Figure 7 are those for each of the time increments and the plot on the right is the mean of the plots shown. On this night, the wave amplitude and direction was quite variable throughout the night. Note that at most all altitudes the degree of damping varies from undamped to saturated.

On this night, vertical winds (w') were studied as well as T and T' from the lidar. Figure 8 is a plot of the vertical winds and temperature during a high frequency wave period. The upward propagating wave shown at 86 km indicates a phase condition between T' and w' which is consistent with a freely propagating wave. The w' leads T' by ~ 90 degrees. At 94 km however (the upper plot), the amplitude has decreased to $<1/3$ the initial amplitude in both T' and w' . Also, it is important to note that w' is almost in phase with T' , an indication of wave damping and a large heat flux

Fig. 8. Time history of vertical wind and temperature for a high frequency wave on Dec. 7, 1999. (Bottom) 86km and (Top) 94 km. Vertical wind and temperature have the same scale.

POTENTIAL ENERGY NORMALIZED, VS. ALTITUDE

The potential energy versus altitude, normalized to 85 km, is plotted for all 4 nights in Figure 9. The data for the four nights of study show similarity in altitude changes in energy. For three of the four nights, the waves appear to be saturated from 85 to near 97 km, above with the slope tends more toward a freely propagating condition. The night of December 7 follows a nearly freely propagating energy trend up to 93 km, becomes severely damped for 3-4 km, and then back to saturated near the top of the plot (and data).

Fig. 9. Wave potential energy vs. altitude as normalized to 85 km. The change in potential energy vs. altitude for a freely propagating wave and saturated conditions are also shown.

The temperature uncertainties are larger near the bottom and top of the data domain due to the smaller Na densities at those altitudes. The integrated temperature errors for the 5 km altitude bins for these nights is typically $< 1/3^\circ \text{C}$ and it is not believed the error biases the slopes of the potential energy curves shown in Figure 9, but further study is needed to totally understand this effect.

SUMMARY

In summary, we have made a detailed analysis of data from correlative airglow and Na temperature/wind lidar measurements from both Albuquerque, NM and Maui, HI, with two nights' data from each station. Significant wave damping is indicated by all waves on all nights. There is a hint that wave stability may be related to the conditions contributing to the damping. Significant accelerations of $\sim 100 \text{ m/s/day}$ is evident in the damping conditions.

In a separate study, these data are being used to study the airglow signatures and degree of damping as predicted by a new model study of OH and O_2 Atmospheric airglow, the amplitudes in the respective intensity perturbations and phases between layers for given damping conditions [Liu and Swenson, 2002].

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