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Maximum altitude penetration of atmospheric gravity waves observed during ALOHA-93

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Abstract. Atmospheric Gravity Waves (AGWs) are subject to altitude propagation limits which are governed by the diffusion processes. Diffusion times and scales which exceed the wave period and wavelength define the limiting domain for AGWs. An expression is presented which defines the upper altitude limit to which AGWs can propagate given vertical diffusion constraints of the atmosphere. Airglow, lidar, and radar measurements are combined to characterize the intrinsic AGW parameters in the 80-105 km altitude region. A subset of AGWs (17) observed by airglow imagers during the ALOHA-93 were made when simultaneous wind measurements were available and intrinsic wave parameters were calculated. The limiting altitude of propagation for these measured monochromatic waves is calculated to range from 110-150 km (with a mean limiting altitude of 130 km). The altitude limit is necessarily lower for waves with short vertical wavelengths and longer intrinsic periods. This observation is important for a large number of issues including energetic considerations regarding thermospheric heating in models which consider upward propagating AGWs (and energy flux) of tropospheric origin. This limited data base should be expanded for statistical significance in future work.

Introduction

The altitude to which AGWs can penetrate is an important consideration in modeling the dynamics and energetics of the atmosphere. AGWs cannot propagate in an atmosphere where the vertical velocity of momentum diffusion exceeds the vertical phase velocity of the waves. In regions where diffusion is the dominant transport process, the wave perturbations are damped with the degree of damping dependent on diffusivity and the intrinsic vertical phase speed of the wave. Consequently, the momentum and energy fluxes generated by vertically propagating AGWs are necessarily deposited below the altitude of maximum penetration as defined by the diffusion constraints and the intrinsic parameters of the wave. Radar observations from Adelaide by Vincent [1984] have shown that ~70% of the energy flux carried in the measured spectrum of AGWs is carried by waves with a period <1.25 hours. Imagers and lidars measure the intrinsic AGW parameters in the 80-105 km altitude region, but not above 105 km. In this study, the altitude limit to which the observed monochromatic features can propagate is determined for a number of waves observed during ALOHA-93. This vertical limit is an 'upper' limit based on diffusion considerations only. Waves can be ducted or dissipate for other reasons, but here we are addressing the issue of propagation regarding diffusion only.

Waves observed by imagers typically exhibit large vertical wavelengths (>10 km) and short periods (< 1 hour) and so are likely to penetrate to high altitudes because their vertical phase velocities are large. Horizontal wavelengths ranging 10 km < λ_z < 300 km are readily observed in a given airglow image. Regarding the sensitivity of OH airglow, the S/N typically is typically >50 so that intensity contrasts of a few % are readily observed. The OH airglow intensity enhancement relative to the AGW perturpations of temperature integrated over the layer is large (~5-10), [see Walterscheid et al., 1987 for example]. In this paper we compute the maximum altitude limit for 17 monochromatic AGWs observed with airglow imagers on three different nights during ALOHA-93. The altitude of maximum propagation data is presented with respect to intrinsic wave parameters.

Analysis

It has long been recognized that viscous effects arising from the diffusion of energetic molecules and from

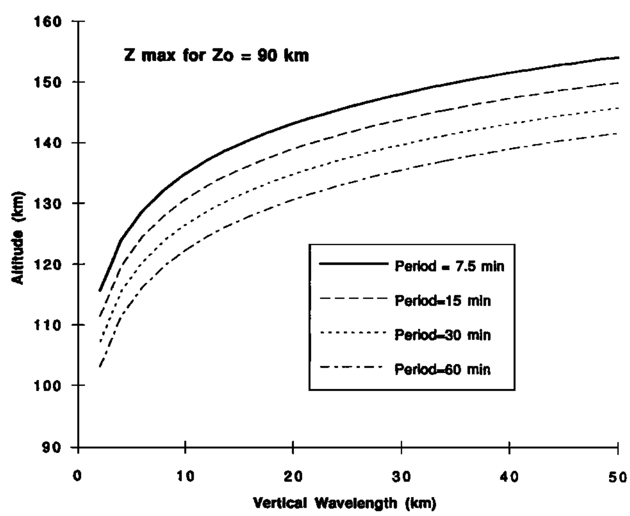

Figure 1. A plot of Z_{max} versus λ_z for a family of T_{In}, where T_{In} = 60, 30, 15, and 7.5 minutes respectively, using equation (4) in the text.

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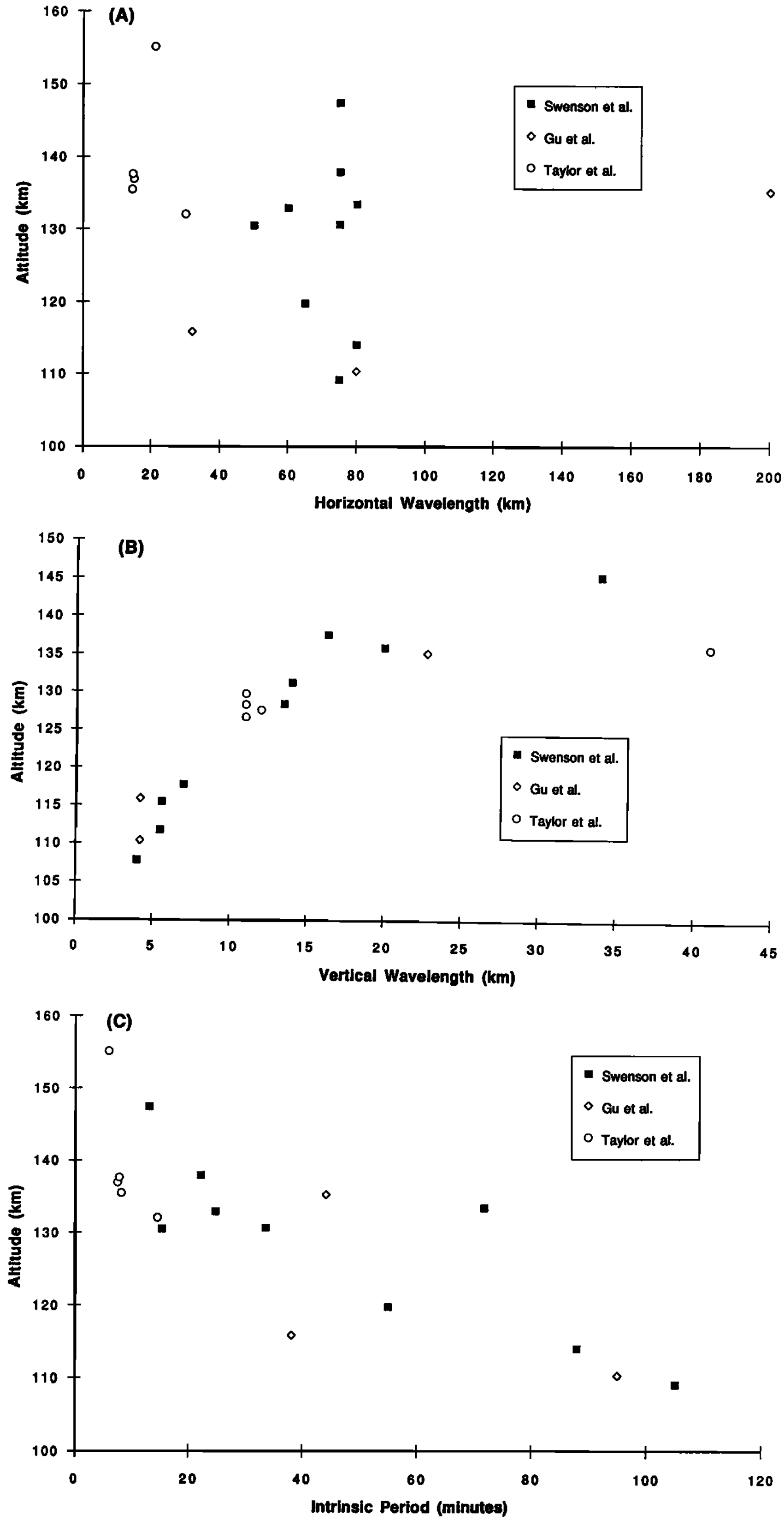

Figure 2. A plot of altitude of Z_{max} for 17 waves, a sample of which were measured during the ALOHA-93 campaign. The mean Z_{max} penetration for the reference waves is 130 km. Plot (a) is versus horizontal wavelength, (b) vertical wavelength, and (c), intrinsic period.

turbulence play an important role in gravity wave propagation [e.g. Hines, 1968 and 1970]. In the upper atmosphere diffusion can lead to severe attenuation of the wave by transporting energy and momentum from one region of the wave system to another in a partially chaotic way. In a region characterized by an effective diffusivity (D), a wave of intrinsic frequency (ω) and vertical wave number (m) will be severely damped when the effective vertical diffusion velocity (mD) of particles experiencing the wave motion exceeds the vertical phase speed of the wave (ω/m). Thus the damping limit for the wave is given by

$$mD_{max} = \omega/m \quad (1)$$

or

$$D_{max} = \omega/m^2 \quad (2)$$

where D_{max} = molecular diffusion coefficient limit for a given AGW. This simple damping criterion can be derived directly from the equations of motion by comparing the relative magnitudes of the main viscous and inertial terms [e.g. Gossard and Hooke, 1975, pp. 218-219].

In the lower atmosphere eddy diffusion caused by turbulence [Hodges, 1967 and 1969: Hines, 1970] and perhaps by nonlinear wave-wave interactions [Weinstock, 1976 and 1990; Gardner, 1994] makes the dominant contribution to the atmospheric diffusivity. However in the upper atmosphere where the molecular mean free paths are large, molecular diffusion dominates. The altitude distribution of molecular diffusivity is inversely proportional to density and can be approximated by:

$$D = D_o \cdot e^{(z-z_o)/H} \quad (3)$$

where H = scale height and D_o is the diffusivity at altitude z_o. Combining expression (1) - (3), the expression for Z_{max} becomes:

$$Z_{max}=z_o + H \cdot \ln(\omega / m^2 D_o)=Z_o + H \cdot \ln(\lambda_z^2/2\pi T_{In} D_o) \quad (4)$$

By noting that $m = 2\pi/\lambda_z$ where λ_z = vertical wavelength, $\omega = 2\pi/T_{In}$, Z_{max} can be defined in terms of the measured parameters, i.e., the vertical wavelength and the intrinsic period. Figure 1 is a plot of Z_{max} vs. λ_z for a family of T_{In} where Z_o = 90 km. This plot suggests that for AGWs with $T_{In} \le 60$ minutes and $\lambda_z < 50$ km, $Z_{max} < 150$ km .

The vertical and horizontal wave numbers are related through the Boussinesq approximation to the gravity wave dispersion relationship, i.e.

$$m^2 \sim h^2 (N - \omega)^2 / (\omega^2 - f^2), \quad (5)$$

where N is the Brunt-Vaisala frequency, f is the inertial frequency, $h = 2\pi/\lambda_H$ and λ_H is the horizontal wavelength [Gossard and Hooke, 1975]. Compressibility of the atmosphere is considered negligible in this approximation. Z_{max} can also be calculated in terms of λ_H using equation 5 .

By using equation (4) with D_o calculated from a model atmosphere at Z_o = 87 km, 90 km, and 95 km for OH, Na and OI (5577 Å) airglow images respectively ar d the Boussinesq approximation for the dispersion relationship, Z_{max} was calculated for the AGWs for which the λ_H and T_{In} were measured. A model atmosphere calculated H of 6 km at Z_o was used. The data used to calculate Z_{max} were obtained from Table 1 in Gu et al. [this issue], Table 1 in Swenson et al. [this issue], and Table 1 in Taylor et al. [this issue]. Note λ_H and observed horizontal phase speed were measured by the imagers. T_{In} was calculated by combining phase measurements with wind observations made by the Haleakala lidar and Kaiui MF radar as discussed in these data references. The results are plotted in figure 2.

The observed AGWs predict virtually no relationship between horizontal wavelength and Z_{max} (figure 2(a)). We do note a very definite relationship between Z_{max} , λ_z (figure 2(b)), and T_{In} (figure 2(c)). As expected, the maximum penetration altitudes are lower for T_{In} large and λ_z small, i.e. for the slow vertical phase speed waves. The waves with a long period do not penetrate to high altitudes as diffusion processes destroy the wave, and similarly, waves with a short vertical wavelength have a spatial scale over which (vertical) diffusion dominates at a relatively low altitude. In perspective, these AGWs cover the entire sky of an airglow imager (radius > 300 km) and often dominate the spatial view observed for extended flight legs (~few 1000 km) near the islands, the details of which are presented in the referenced papers [Gu et al., Swenson et al., and Taylor et al. this issue].

Summary

The altitude of maximum penetration identifies the altitude regime to which dynamic and energetic considerations should be made for the class of waves measured and reported here. Examination of diffusion considerations suggest that AGWs propagating upward through the 90 km altitude region with $T_{In} \le 60$ minutes and $\lambda_z < 50$ km, have a maxiumum vertical propagation limit of 150 km. The Z_{max} is directly related to vertical wavelength (i.e. the larger λ_z, the higher Z_{max}) and indirectly related to T_{In}. The Z_{max} for a number of AGWs observed on three separate days during the ALOHA campaign (17 total) was calculated and presented with respect to λ_H, λ_z, and T_{In}. It should be noted that the data presented here is a relatively small sample and only represents what was observed during ALOHA-93 on three nights of observations near the islands. We plan to expand on this data base. As the AGW intrinsic parameters and energy flux can be well characterized in the 80-105 km altitude through the remote sensing signatures available in this layer, the altitude extent to which the waves can influence the atmosphere (and deposit their energy) can be better characterized.

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