Characteristics of Quasi-Monochromatic Gravity Waves Observed with Na Lidar in the Mesopause Region at Starfire Optical Range, NM

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[1] The University of Illinois Na wind/temperature lidar data collected at the Starfire Optical Range, NM, between Jan. 1998 and May 2000 was used to extract the dominant monochromatic gravity waves. By using simultaneously measured horizontal wind and temperature profiles, the vertical wavelengths (l_z), (T_i), and propagation directions were determined using the hodograph method. A total of 700 monochromatic gravity waves were analyzed from ~300 h of observations. It was found that 84.4% of the waves were propagating upwards. The mean l_z was 12.6 km and 9.9 km for upward and downward propagating waves, respectively, and showed a bimodal distribution with the largest number of waves at 15–17 km and 7–9 km. The mean T_i is ~10 h. There is no dominant direction of propagation. For waves with l_z<11 km, the percentage of upward propagating waves is lower (71%).

INDEX TERMS: 3334 Meteorology and Atmospheric Dynamics; 0341 Middle atmosphere dynamics (0341, 0342); 3360 Remote sensing; 3384 Waves and tides.


1. Introduction

[2] Atmospheric gravity waves (GWs) play a major role in the dynamics of the atmosphere in the mesopause region. Observations and statistics of data are needed to characterize the GWs’ spectral, temporal, and spatial variations. Quasi-monochromatic (QM) GWs are frequently observed with airglow imagers, lidars and radars. The QM waves observed with imagers typically have short horizontal wavelength (l_x) and high frequency [Hecht et al., 2001; Walterscheid et al., 1999], while those observed by radars and lidars typically have long l_x and low frequency [GavriloV et al., 1996].

[3] Hodograph method has been widely used to analyze QM waves observed by radar and lidar. GavriloV et al. [1996] used this method with MU radar 3-D wind data and showed that there were relatively more waves with larger l_x. Nan-borothiri et al. [1996] used both MU radar horizontal wind and lidar Na density data and obtained GW’s propagation directions. The l_x of QM waves can be related to the intrinsic frequency through GW’s dispersion relations [Gardner and Voélz, 1986]. Swenson et al. [1995] showed that GW’s with large l_x can penetrate to higher altitudes.

2. Data Analysis

2.1. Data

[5] There are a total of 45 nights or 300 h of wind and temperature data acquired between Jan. 1998 and May 2000. The data between 84 km and 104 km were used. The original data was smoothed to 1 km in the vertical direction and temporally averaged every 30 min. Therefore, only the waves with 2 < l_z < 20 km and period between 1 h and 20 h were considered.

2.2. Hodograph Method

[6] A wave propagating in x–z plane can be expressed as,

\[ \vec{u'}(\vec{x}, \vec{y}, T') = e^{i(w+nf)/2H} \Re \left[ (\hat{\vec{u}}, \vec{v}, T') e^{i(kmz-\omega t)} \right], \]

where \( \vec{u'} \) is the in-phase wind along the wave propagation direction, \( \vec{v} \) is the quadrature-phase wind perpendicular to the wave propagation direction, \( T' \) is the temperature perturbation, \( k \) and \( m \) are horizontal and vertical wavenumbers, respectively, and \( \omega \) is the frequency. The GW polarization relations are

\[ \hat{\vec{v}} = -i(f/\omega)\hat{\vec{u}}, \]

\[ \hat{T} = H[|m| + 1/(2H)](\vec{w}^2 - f^2)/(\omega kR)\hat{\vec{u}}, \]

where \( H \) is the scale height, \( R \) is the gas constant and \( f \) is the inertial frequency. In the Northern Hemisphere where \( f > 0 \), (2) shows that \( \hat{\vec{v}} \) will lead \( \vec{u} \) for upward propagating waves, i.e. the \( (\vec{w}', \vec{v}') \) vector will rotate clockwise with increasing altitude. Similarly, according to (3), for upward propagating waves \( (m < 0) \), \( \hat{T} \) will lead \( \vec{u} \) for waves propagating in positive x direction, and the \( (\vec{u}', \vec{T}') \) vector will rotate clockwise with increasing altitude. These rotations are reversed for waves propagating in the opposite direction. This information can be used to determine both the horizontal and vertical propagation directions.

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2.4. Analysis Technique

[7] The intrinsic frequency can be calculated by the amplitude ratio between \( \hat{u} \) and \( \hat{v} \) based on (2). The background shear perpendicular to the wave’s horizontal propagation direction can affect this estimation [Hines, 1989]. To minimize this effect, we defined a factor \( D = |1/N|(dV/d\varphi)/(f_0/\omega) \), where \( N \) is the buoyancy frequency. For waves with \( D > 0.3 \), the wind shear effect was considered significant and they were excluded in the analysis.

2.3. Gravity Wave Model

[8] The QM waves are modeled as [Yang, 1998],

\[
U_m' = U_0 e^{i(z-z_0)} \cos[m(z-z_0) + \theta_u],
\]

\[
V_m' = V_0 e^{i(z-z_0)} \cos[m(z-z_0) + \theta_v],
\]

\[
T_m' = T_0 e^{i(z-z_0)} \cos[m(z-z_0) + \theta_t],
\]

where \( \beta \) is the growth factor, \( z_0 = 94 \) km, \( U_m', V_m', T_m' \) are perturbations of zonal and meridional wind and temperature with vertical wavenumber \( m \), respectively.

[9] The amplitudes of the wind component along the major and minor axes of the polarization ellipse, \( |\hat{u}| \) and \( |\hat{v}| \), and the azimuth \( \varphi \) of the major axis can be calculated by using the following formula [Gavrilov et al., 1996],

\[
\varphi = \frac{1}{2} (\pi n + \arctan \frac{2F_0}{V^2 - U^2}),
\]

\[
2|\hat{u}|^2 = U^2 + V^2 + \left[(V^2 - U^2)^2 + 4F_0^2\right]^{1/2},
\]

\[
2|\hat{v}|^2 = U^2 + V^2 - \left[(V^2 - U^2)^2 + 4F_0^2\right]^{1/2},
\]

where \( F_0 = UV \cos(\theta_u - \theta_v) \). The integer \( n = 1 \) when \( V < U \). When \( V > U \), \( n = 0 \) and \( 2 \) for \( F_0 > 0 \) and \( F_0 < 0 \), respectively, in order for \( 0 \leq \varphi \leq \pi \).

2.4. Analysis Technique

[10] The procedure of the analysis is to first determine the \( \lambda_z \) of the dominant wave from the perturbation power spectrum, then fit the perturbation according to GW model to derive other intrinsic parameters. The first step is to derive the wind and temperature perturbations. Linear fits on each nightly mean wind profiles were used as the background winds. A fourth order polynomial fit on each nightly mean temperature profile was used as the background temperature. The perturbation profiles were obtained by subtracting the backgrounds from the original profiles. A linear trend in altitude of each profile was then removed to minimize the contamination of tidal oscillations and long \( \lambda_z \) waves.

[11] The \( \lambda_z \) of the dominant wave was determined by finding the peak in the mean power spectrum of the zonal wind, meridional wind and the scaled temperature for each set of perturbation profiles. The temperature perturbation was scaled to make it comparable to and in the same unit with the wind perturbation, by multiplying it with \( g/(T_0N_0) \), where \( g \) is the gravity acceleration, \( T_0 \) and \( N_0 \) are the nightly mean temperature and buoyancy frequency, respectively. The spectral resolution was enhanced by padding the perturbation profiles with zeros prior to computing their spectra. A \( \lambda_z \) was accepted when its corresponding peak power was above the 95% confidence level and an empirically determined threshold. The threshold was used to make sure only waves with significant amplitudes were extracted.

[12] After the \( \lambda_z \) was determined, the wave parameters were deduced by fitting the GW model (4)–(6) to both wind and temperature perturbation profiles. The major axis angle \( \varphi \) was then calculated, and the horizontal coordinates were rotated so that the \( x \)-axis was along the major axis. This fitting was then repeated in the new coordinates and a new \( \varphi \) was obtained. When \( \varphi \) converged to within 0.1°, the iteration was stopped and the first dominant wave was extracted. This wave was then subtracted from the perturbation profiles and the above process was repeated to find the next dominant wave. On average, 2 to 5 waves can be reliably extracted from each profile [Yang, 1998]. Waves extracted after the 2nd wave usually had very small amplitude. In this study, we only considered the 1st and 2nd waves.

3. Results and Discussions

3.1. An Example Case

[13] Figure 1a shows the hodograph for zonal and meridional winds and their wave fits. This inertial GW with \( \lambda_z \) of 14.7 km was observed at 3:30 UT on Aug. 12, 1999. The
3.2. Distribution of $L_t$ (all accuracy of the extracted long wavelength waves (Figure 5a) has a bell shaped distribution, with the peak at 10–11 km. The intrinsic period between the 1st and the 2nd waves extracted from the nominal conditions, the SDT does not have strong influence to the extracted QM waves. Nevertheless, the SDT amplitude in the real atmosphere can be much stronger in any individual night. Therefore some of the extracted waves with $\lambda_z$ between 15–17 km may be contaminated. In addition, the presence of SDT also increased the uncertainty of extracted intrinsic period.

The histogram of $\lambda_b$ (Figure 4a) does not show a bimodal distribution. The largest number of waves have $\lambda_b$ between 500 and 2000 km. There is no dominant direction of propagation (Figure 4b), although there is a slight preference toward the northeast and southeast. The intrinsic period (Figure 5a) has a bell shaped distribution, with the peak at around 10–11 h.

3.3. Limitation of the 20 km Altitude Range

The 20 km altitude range of the data may limit the accuracy of the extracted long wavelength waves ($\lambda_z > 10$ km). This is due to the possible contamination by waves with $\lambda_z > 20$ km and $< 40$ km. These waves cannot be extracted with the 20 km data range but their effect cannot be fully removed by detrending. Such waves include the semidiurnal tide (SDT), which has a $\lambda_z$ between 20–40 km in winter [Franke and Thorsen, 1993]. The influence of the SDT in the summer is expected to be small because of its much longer $\lambda_z (> 100$ km). In winter, the SDT may contaminate the 15–17 km QM waves we obtained.

To address this issue, we performed Monte-Carlo simulations to examine the effect of SDT on the extracted waves. We used the Jan. SDT data from the Global Scale Wave Model (GSWM) [Hagan et al., 1999], which has a temperature amplitude of 5–15 K from 85 to 100 km. This amplitude is comparable to or larger than observations [Palo et al., 1997; States and Gardner, 2000]. We found that it was not large enough to produce erroneous waves with our algorithm because its power spectrum didn’t exceed our threshold (about 60% too low). This indicates that under nominal conditions, the SDT does not have strong influence to the extracted QM waves. Nevertheless, the SDT amplitude in the real atmosphere can be much stronger in any individual night. Therefore some of the extracted waves with $\lambda_z$ between 15–17 km may be contaminated. In addition, the presence of SDT also increased the uncertainty of extracted intrinsic period.

Our simulation also showed that the presence of SDT did not have noticeable effect on short $\lambda_z$ waves. We therefore separately plotted histograms for waves with $\lambda_z < 11$ km only, i.e. waves that were not contaminated. Their mean parameters are also listed in Table 1. There are 223 (71%) waves propagating upward and 91 (29%) waves downward. Com-

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### Table 1. Mean Values of Intrinsic Period $\tau$, Vertical and Horizontal Wavelengths ($\lambda_z$ and $\lambda_b$) of Extracted QM Waves for All Waves and for Waves With $\lambda_z < 11$ km

<table>
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<tbody>
<tr>
<td>$\tau$ (all $\lambda_z$) (h)</td>
<td>10.5</td>
<td>8.5</td>
<td>10.2</td>
</tr>
<tr>
<td>$\tau$ ($\lambda_z &lt; 11$ km) (h)</td>
<td>10.3</td>
<td>8.7</td>
<td>9.8</td>
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<tr>
<td>$\lambda_z$ (all $\lambda_z$) (km)</td>
<td>12.6</td>
<td>9.9</td>
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<tr>
<td>$\lambda_z$ ($\lambda_z &lt; 11$ km) (km)</td>
<td>8.0</td>
<td>8.6</td>
<td>8.2</td>
</tr>
<tr>
<td>$\lambda_b$ (all $\lambda_z$) (10^4 km)</td>
<td>2.25</td>
<td>1.32</td>
<td>2.11</td>
</tr>
<tr>
<td>$\lambda_b$ ($\lambda_z &lt; 11$ km) (10^4 km)</td>
<td>1.42</td>
<td>1.19</td>
<td>1.36</td>
</tr>
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Figure 3. Same as Figure 2 except are shown separately for the 1st (a) and the 2nd (b) extracted waves.

Figure 4. Histograms of (a) horizontal wavelengths (b) and propagation direction. North is up and east is right. Darker (lighter) shading indicates upward (downward) propagating waves.

Figure 5. (a) Histograms of intrinsic periods for (a) all 700 extracted waves and (b) waves with $\lambda_z < 11$ km. Darker (lighter) shading indicates upward (downward) propagating waves.
pared with the distribution of all waves, the intrinsic period (Figure 5b) shows a similar bell shaped distribution. The horizontal wavelength (Figure 6a) has a narrower distribution with a smaller mean value. The propagation direction (Figure 6b) also shows similar distribution, with north-east and south-west being the most frequent directions.

4. Summary

A total of 300 h of Na wind/temperature data were used to characterize the quasi-monochromatic inertial gravity waves with the hodograph method. A total of 700 waves were obtained. The majority of them (84.4%) propagated upwards. The percentage is similar to that obtained by Lintelman and Gardner [1994], who computed the unambiguous vertical wavenumber spectra to determine the fraction of energy propagating upward and downward based on 350 hours of Na lidar data at Urbana, Illinois.

The $\lambda_z$ showed a bimodal distribution with the most frequently observed waves having $\lambda_z$ of about 15–17 km and 7–9 km. We have verified that the 15–17 km and 7–9 km waves are not harmonically related. The possible contamination to the 15–17 km waves by waves with $\lambda_z > 20$, such as SDT is minimized by removing the linear trend in altitude. Monte-Carlo simulations with GSWM data suggest that this contamination is not likely a significant source to the extracted 15–17 km wave.

The distribution of amplitudes versus vertical wavelengths and the distribution of intrinsic phase speed versus in-phase wind fall within the linear instability limit (not shown). The waves with relatively large $\lambda_u$ usually have relatively large amplitudes. They can be more frequently observed than those with relatively small $\lambda_u$. The bimodal distribution of $\lambda_z$ is very intriguing. Most of the 1st extracted waves, i.e. the dominant waves, have $\lambda_z$ of 15–17 km. There is very little waves in the 12–14 km range. It may be related to the wave source and filtering through the middle atmosphere.

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