Investigation of vertical wavenumber and frequency spectra of gravity-wave-induced vertical wind and temperature perturbations

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Abstract: 233 hours of high-precision vertical wind and temperature measurements in the mesosphere and lower thermosphere (MLT) were used to study the spectra of gravity wave perturbations in the mesopause region. The temperature spectra are generally consistent with the theoretical predictions of gravity wave theory. The averaged slope of the frequency (*f*) spectra is –1.83±0.08, while the slope of the vertical wavenumber (*m*) spectra is –3.0±0.1. The observed *f* and *m* spectra of vertical winds are both very shallow. The averaged slope of the *f*-spectra is –0.4±0.1, and the averaged slope of *m*-spectra is –1.01±0.04. These spectral characteristics of gravity waves provide important insights into the mechanisms that are primarily responsible for wave damping and dissipation in the atmosphere.

Keywords: Coherent Laser Radar, etc.

1. Introduction

Gravity waves play a critical role in the middle and upper atmosphere due to their dominant influences to the residual circulation and their ability to transport energy, momentum and constituents and affecting thermal structure of the atmosphere [1]. Despite of the numerous theoretical and observational studies that aim to advance our understanding of such waves, there is still considerable disagreement about the dominant gravity wave saturation and dissipation processes. Consequently, gravity wave effects have been poorly parameterized in existing global circulation models. Currently, several proposed mechanisms that dominate gravity wave saturation and dissipation processes include: shear and convective instabilities, non-linear effects of wave-wave interaction, scale-dependent diffusion and diffusion filtering theory (see review in [2]).

Gardner [3] compared the different theories and compiled a table of predictions on the spectra of the horizontal and vertical winds. These theories can be evaluated by comparing measured spectra to the predictions. Some of the theories are founded on the assumption that the vertical wind and temporal motions (m, ω) are separable. Additionally, some of the theories require that the horizontal motions are independent of azimuth - that is: (h, ϕ) are separable. In this study, we make high resolution measurements of the vertical wind (w) and temperature (T) in the mesosphere and lower thermosphere which are used to calculate the vertical (m) and temporal (ω) spectra. With these spectra, we evaluate the accuracy of each of the theories.

2. Observations

The data used in this investigation were collected from the Student Training and Atmospheric Research (STAR) Na Doppler Lidar located at North of Boulder. This STAR lidar employs a classical dye-laser-based master oscillator power amplifier, a Newtonian telescope receiver, and modernized data acquisition and control systems, and uses the 3-requency technique to infer temperature, radial wind and Na density in the mesosphere and lower thermosphere (detailed principles can be found in [4]). Originally constructed by graduate students in summer 2010, this STAR lidar received several upgrades in the following years. In 2011, significant improvements of the receiver efficiency [5] enabled this STAR lidar to obtain very high resolution data. In 2013 the dual acoustic-optic frequency shifters were upgraded from ±480MHz to ±750MHz, making the STAR lidar more sensitive for vertical wind, temperature, and Na density measurements.

The raw photon counts were collected in the temporal and spatial resolutions of 3 s and 24 m. Temperatures and winds are then derived using the raw photon counts smoothed with a 15 min (full width) Hamming window and the window is shifted at a step of ~5 min. The raw photon counts are binned into 0.96 km to retrieve the temperature and winds in order to further increase the precision. The measurement uncertainties in the vertical wind and temperature are ~0.4 m/s and ~0.8 K respectively near the Na layer peak (~90 km). 233 hours of observations over 21 nights from August of 2013 to January of 2014 were selected for this study, which average approximately 11 hours of consecutive data each. The shortest night of data is approximately 7 hours long and subsequently the longest resolvable wave period in the frequency spectra was 14 hours. The altitude range of the data used is 85–105 km, which determines longest resolvable wavelength in the vertical wavenumber spectra to be approximately 60 km.

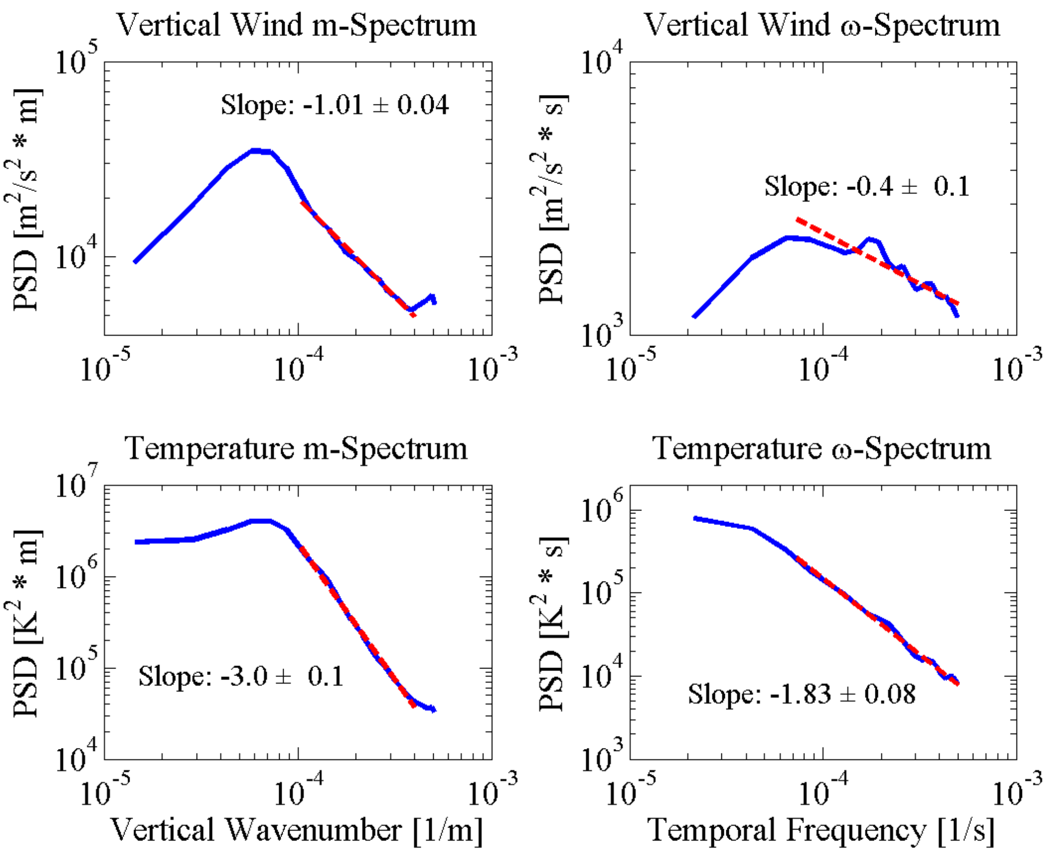
3. Measured Vertical Wavenumber and Frequency Spectra of Gravity Waves

Prior to spectral analysis, we removed extreme outliers caused by measurement errors from the data set and replaced them with interpolated values using a simple plate metaphor method. These data occurred at the extremes of the altitude range where the sodium density was occasionally insufficient. The perturbations of the temperatures and winds are then derived by subtracting the vertical and temporal means. In addition, to reduce the power leakage introduced by large-scale waves such as tides and planetary waves into the gravity wave spectra, we removed linear trends in both spatial and temporal domains. The linear detrend primarily affected the calculated spectra by removing power from the longer vertical wavelengths and lower frequencies essentially damping out the effect of long period waves. Following these initial processing steps, we conducted spectral analysis on the data.

We calculate the power spectral densities using a prewhitening and postcoloring method [3]. This method is employed to reduce sidelobe leakage from the finite length of the rectangular window. The 2nd order of AR model was chosen based on the final prediction error (FPE) criterion. The vertical wavenumber spectra at each time and frequency spectra at each altitude were first calculated, and then averaged to generate episode-mean wavenumber and frequency spectra, respectively. The episode-mean vertical wavenumber spectra and frequency spectra are shown in Figure 1. We also computed the average spectra over the entire 21-night dataset which are shown in Figures 2 and 3. In Figure 2 the spectra were calculated after only removing the mean while in Figure 3 the spectra were calculated after the linear detrend. We fit a power-law model to each of the spectra within the saturated regime. The estimated spectral index is the "slope" of the power-law fit and each of the indices for the four spectra are reported in Table 1. We find that the measured m-spectra fall into close agreement with the spectra measured at Starfire Optical Range using a similar technique.

Table 1. Spectral Indices of Measured Spectra

Data Set	Spectrum	Spectral Index	LIT Prediction	DFT Prediction	SCT Prediction
$Temperature$	m-Spectrum	-3.0 +/- 0.1	-3	-3	-3
	ω-Spectrum	-1.83 +/- 0.08	-p (p = 2)	-p (p = 2)	-2
$Vertical\ Wind$	m-Spectrum	-1.01 +/- 0.04	-3	5-2p (p = 2)	1
	ω-Spectrum	-0.4 +/- 0.1	N/A	0	0



4. Discussion

Gardner 1996 [3] compares existing theories of gravity wave dissipation and their predictions. The theories considered include linear instability (LIT), saturated-cascade (SCT), diffusive filtering (DFT), diffusive damping, and Doppler spreading. The competing theories can be tested by comparing their predictions. In the table of that paper, he compares the spectral indices predicted by the different theories. Only three make predictions about the vertical wind gravity wave spectrum and those predictions are summarized in Table 1 alongside the measured spectral indices. It is apparent that the established consensus on the temperature spectrum is supported by our data. All three of the theories predict a vertical wavenumber spectral index of -3 for gravity waves in the saturated regime ($m > m_*$). In addition, they predict a temporal spectral index of -2. We measured -1.83 ± 0.08 which is slightly shallower than predicted. The agreement between our measurements and established theory reaffirms our assertion that the measured spectra are calculated accurately and that we have minimized signal pollution.

Similar to the findings in Gardner 1998 [4], we find that the spectral indices for the vertical winds are much shallower than the temperature spectra. According to Gardner [3]: "If (m, ω) separability holds, then the shapes of the horizontal and vertical wind spectra will be identical. Only the magnitudes will differ." The measured vertical wind spectra are significantly shallower than the observed temperature spectra and agree well with Gardner's findings. Therefore, we reaffirm Gardner's claim that the (m, ω) spectra are not separable. This finding challenges the fundamental assumptions of Dewan and Good's Linear Instability Theory, which is founded on the assumption that the m and ω spectra are separable. Furthermore, we see that the vertical wind m-spectrum (-1.01 ± 0.04) is in good agreement with Gardner's findings at Starfire Optical Range (-1.08 ± 0.04). We can see that the spectral index estimated from the vertical wind m-spectrum does not agree with the predictions made by any of the theories. Similarly, the observed vertical wind ω-spectrum (-0.4 ± 0.1) is much shallower than the intrinsic spectrum predicted by DFT. This discrepancy suggests that either measurement error has significantly affected the vertical wind spectra or that Doppler shifts and/or critical layer effects could alter the intrinsic spectrum.

5. Conclusions

Using the high-precision vertical wind and temperature measurements in the mesosphere and lower thermosphere (MLT), we studied the spectra of gravity wave perturbations in the mesopause region. We investigated the gravity wave spectra in the measured temperatures and found that they are generally consistent with the theoretical predictions of gravity wave theories. Such agreement reaffirms our assertion that the measured spectra are calculated accurately and that we have minimized signal pollution. We also investigated the gravity wave spectra in the measured vertical winds. The averaged slope of the frequency (*f*) spectra is –1.83±0.08, while the slope of the vertical wavenumber (*m*) spectra is –3.0±0.1. The observed *f*- and *m*- spectra of vertical winds are both very shallow, compared to the observed temperature spectra. This result suggests the *f*- and *m*-spectra are not separable and therefore challenges the fundamental assumptions of Dewan and Good's Linear Instability Theory. Although our results on the gravity wave vertical wind spectra are quite similar to Gardner's finding at Starfire Optical Range, there is significant discrepancy between the theoretical and measured spectral shapes. This discrepancy suggests that either measurement error has significantly affected the vertical wind spectra or that Doppler shifts and/or critical layer effects could alter the intrinsic spectrum.

6. References

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