9.5 OBSERVATIONS OF TROPOSPHERIC. CONVECTIVELY GENERATED GRAVITY WAVES FROM ATMOSPHERIC PROFILING PLATFORMS

Daniel R. Adriaansen * University of North Dakota, Grand Forks, ND

M. J. Alexander NWRA/Colorado Research Associates Div., Boulder, CO

Gretchen L. Mullendore University of North Dakota, Grand Forks, ND

1. INTRODUCTION

In an idealized setting, convectively generated gravity waves have been shown to initiate new storms in the forward environment of a squall line (Fovell et al. 2006). Both high and low frequency waves resulting from tropospheric deep heating and convective processes contribute to this new storm development. Low frequency waves map onto two different modes (mode 1 and mode 2) as a result of latent heating and cooling occurring in the convective region (Nicholls et al. 1991). Mode one is simply a tropospheric deep subsidence region created as a byproduct of the heating within the convective core. Mode two is particularly instrumental in the convective initiation process, as it serves to develop a so called 'cool moist tongue' (Fovell et al. 2006). This layer of gently lifted air in the 3-5 km laver approaches saturation, effectively primina the environment for further development.

The particular trigger of interest for new convective development comes in the form of high frequency gravity waves. These waves are generated by cell regeneration processes as well as latent heating, and travel outward from the convective region. Unlike the low frequency waves, these high frequency waves can propagate vertically and also become trapped in the forward environment. This trapping plays a significant role in initiating new storms from the nearly saturated layer of air created by the mode 2 low frequency waves (Fovell et al. 2006). If parcels in the cool moist tongue encounter a series of gravity wave updrafts, enough lifting for condensation and cloud growth can occur. While the high and low frequency wave interaction appeared to foster convective initiation within the simulation, observations of such an event are lacking.

Prior studies have employed a variety of methods to observe gravity waves in the atmosphere. However, traditional gravity wave observational platforms are often inadequate for observing mid-tropospheric waves as a result of being limited to the surface and boundary layer (e.g. temperature and pressure traces), being limited in time (balloon-borne soundings), or being limited by relatively large signal-to-noise ratios (e.g. In this study, we use several wind profilers). observational platforms along with special analysis techniques to describe mid-tropospheric gravity waves caused by deep convection.

The University of Alabama Huntsville operated their Mobile Integrated Profiling System (MIPS) during the Bow echo and Mesoscale convective vortex EXperiment (BAMEX). This platform included both a MPR and a 915 MHz wind profiler, among other instruments. The MIPS intercepted several organized convective events capable of producing the anticipated low and high frequency signals. However, a wind profiler with an operating frequency of 915 MHz proved insufficient for capturing the high frequency waves through the depth of the troposphere. As a result, only data from the MPR were utilized to identify the presence of any low frequency wave activity.

Supplementary data were sought for analysis of high frequency gravity waves. The Tropical Warm Pool, International Cloud Experiment (TWP-ICE) consisted of multiple observation platforms to study the impact of clouds in the tropical warm pool region. The Australian Bureau of Meteorology operated a 50 MHz wind profiler during a significant portion of the TWP-ICE project. Unlike the 915 MHz profiler implemented during BAMEX, the 50 MHz profiler can resolve air motions at much higher altitudes. This makes it a desirable choice for high frequency wave observations, especially during TWP-ICE when organized convection was a common occurrence.

2. RESULTS

2.1 Low Frequency Analysis

Two days were selected from the BAMEX field campaign, when the MIPS was located in a favorable position relative to organized convection (Fig. 1). Case 1 was on 28 May, 2003 and case 2 was on 31 May

^{*} Corresponding author address: Daniel R. Adriaansen, Univ. of North Dakota, Dept. of Atmospheric Sciences, Grand Forks. ND 58202-9006: e-mail: daniel.adriaansen@und.edu



Figure 1: 0.5 degree elevation scan of reflectivity for (a) case 1 (22:45Z) and (b) case 2 (2:40Z). The location of the MIPS relative to the convection is shown near the center of each panel.

2003. In both cases the MIPS was active for a sufficient period of time ahead of the convection to sample the forward environment. The MPR operated as part of the MIPS retrieved profiles of water vapor, temperature, relative humidity and cloud liquid water. The mode 2 signal should appear as an increase in water vapor and relative humidity in the 3-5 km layer, with a decrease in temperature over the same layer. Both of these changes occur as a result of the gentle lifting associated with the mode 2 wave.

Initial evaluation of the temperature, water vapor and relative humidity data revealed subtle signals of mode 2 activity in the forward environment. The temperature field for case 1 was essentially uniform across much of the forward environment. Between 30 km and 50 km from the squall line (SL), there was a very slight cooling in the 3-5 km layer, and a slight warming above 5 km (Fig. 2). As convection neared the MPR, temperature trends became less apparent. These findings were similar to the temperature field for case 2 as well, except



Figure 2: Raw temperature observations from the MPR for (a) case 1 and (b) case 2. Distance from the convection (km) is shown on the x-axis and increases to the right.

for case 2 the trends occurred over a much larger distance ahead of the main convection. The temperature trends in these regions for both days are consistent with mode 2 wave activity.

Water vapor observations from the MPR exhibited slightly different characteristics for each case. For case 1, water vapor did show an increase between 13 km and 40 km from the SL which is consistent with low frequency wave activity. Figure 3a shows that the increase in water vapor occurred throughout all levels, as opposed to the expected 3-5 km layer region anticipated from mode 2 waves. For case 2, the increase in water vapor was seen between 35 km and 55 km from the SL. As convection neared the MPR in case 2, the water vapor field remained relatively constant throughout the column.

Similar to the water vapor observations, the relative humidity field also varied between cases. Case 1 had some interesting features between 30 km and 90 km from the SL. Small regions of relative humidity greater than 50% appeared centered on an altitude of 5 km. These regions of increased humidity may be attributed to high frequency wave activity in the forward environment. Case 2, however, showed a region of much higher relative humidity in the forward environment, also centered on an altitude of 5 km. Values in this region exceeded 90% (Fig. 4b). Although



Figure 3: Raw water vapor observations from the MPR for (a) case 1 and (b) case 2. Distance from the convection (km) is shown on the x-axis and increases to the right.



Figure 4: Raw relative humidity observations from the MPR for (a) case 1 and (b) case 2. Distance from the convection (km) is shown on the x-axis and increases to the right.

these values are indicative of a nearly saturated layer at 5 km similar to mode 2 wave activity, we believe this is in fact the signal of a leading stratiform type system (Storm et al. 2007).

Leading stratiform had an impact not only on case 2, but case 1 as well. Based on the water vapor, temperature and relative humidity fields, leading stratiform was present for a longer period during case 2. The case for leading stratiform is supported not only in the MPR observations, but also satellite imagery and radar as well. One may have noticed the large leading precipitation shield for case 2 in figure 1b. Further highlighting the presence of a stratiform region in the forward environment were zenith infrared temperature measurements taken at the MIPS site. As one would expect, these temperatures showed a broad increase as the convection neared the observation site consistent with an increase in mid and low-level cloudiness.

In situations where leading stratiform is present, it may be nearly impossible to identify low frequency gravity wave signals from convection. This is largely due to the similar thermodynamic characteristics between the mode 2 signal and the stratiform region. Latent heating within the cloud region from ongoing precipitation processes mimics the subsidence warming at altitudes above 5 km. Between the surface and 5 km, evaporative cooling below the stratiform deck from any precipitation that may be occurring can look similar to gentle lifting and cooling as a result of mode 2 signals. This is likely what has been revealed by the MPR observations from BAMEX, rather than the mode 2 low frequency signal.

2.2 High Frequency Analysis

Data from a 50 MHz wind profiler was used to diagnose high frequency wave activity from organized convection on 19 January, 2006. The profiler site was located just to the southeast of the city of Berrimah NT, Australia. Also located at this site was a 920 MHz wind profiler. This boundary layer profiler was used to identify periods when precipitation was present. Identifying periods of rain was necessary due to the increased uncertainty of the 50 MHz profiler during episodes of precipitation. In addition, it helped to identify the time when convection arrived at the profiler site.

In order to perform any spectral analysis on the 50 MHz wind velocity data, several techniques to improve data quality were implemented. Beyond eliminating periods when precipitation was identified, missing data created additional sections where analysis was limited. Extreme outliers not flagged by raw data quality checks were removed as well. For *w*, values lying outside +/- 4σ and for *u*, values outside +/- 5σ were eliminated. After the above procedure, a linear fit was used to interpolate across periods of missing data. To combat high frequency noise in the data a three point running smoother was applied to the data prior to spectral analysis.

Spectral analysis using the S-transform (ST) (Stockwell et al. 1996) was performed on the vertical velocity field to identify a dominant period of oscillation. Unlike a traditional Fast Fourier Transform (FFT), the ST allows for time-frequency representation of a signal, while isolating the real and imaginary spectra. However, the spectrum of one time series from the ST contains noise on the order of 100%. To address this issue, averaging the spectra over many levels can reduce the noise to $1/\sqrt{n}$. Figure 5a shows average spectra of vertical velocity over 14 levels, and figure 5b shows the average spectra for the zonal wind over the same levels. Note that due to the different height and time resolution of the zonal wind, it was necessary to interpolate the zonal wind onto the vertical velocity height and time domain. The dotted line is included to indicate the average value of the tropospheric buoyancy frequency (N), which corresponds to 0.0019 s^{-1} , or roughly a period of about 8.8 minutes. Ideally, more levels extending farther into the troposphere are desired, however the quality of the zonal wind data above 6.5 km decreased dramatically. It is interesting to note that in both the spectra of vertical velocity and zonal wind, a maximum appeared at a period of roughly 16.7 minutes. This value is consistent with previous studies which have indicated ground based periods of 15-20 minutes for convectively generated gravity waves (Vincent et al. 2006).

Of significant importance to our study of high frequency wave observations is the role that they play in



Figure 5: Average spectra from 2137m to 6232m for (a) w and (b) u. Frequency is on the y-axis, in units of $1*10^{-3} s^{-1}$. Convection occurred at 00Z.



Figure 6: Results of the CST analysis. Covariance between u and w is shown in (a), the real part of cov(u,w) in (b), and the imaginary part of Cov(u,w) in (c) for heights from 2137m to 6232m. Frequency is on the y-axis, in units of $1*10^{-3} s^{-1}$. Convection is at 00Z.

convective initiation within the forward environment. Without trapped high frequency waves, parcels in the cool moist tongue within the 3-5 km layer may not achieve saturation and subsequent vertical development. The ST has the ability to spectrally aid in identifying regions where trapped waves may be present. This is accomplished through the calculation of the cross S-transform (CST). The CST is computed by taking the complex conjugate between u and w. The absolute value of the CST between u and w gives the amplitude of the signal common to both fields (Evan and Alexander 2008). By extracting the real part of the complex spectrum, one can obtain information about the cospectrum and momentum flux. Similarly, by extracting the imaginary part of the complex spectrum



Figure 7: Percentage of the real part of Cov(u,w) (a), and percentage of the imaginary part of Cov(u,w) (b). Frequency is on the y-axis, in units of $1*10^{-3} s^{-1}$. Convection occurred at 00Z.

one can gain knowledge about the phase between the two fields. By evaluating the proportion of signal in the real part or imaginary part of the covariance, information about wave trapping can be inferred.

The CST between *u* and *w* shows a strong covariance between the two signals, especially from 22:45 to 23:45Z and again between 20:15 and 21:45Z (Fig. 6). These areas exist in the frequency range typically associated with convectively generated gravity waves. There is an additional maximum from 21:15 to 22:45Z; however this exists at a period of almost 30 minutes which is outside the range for high frequency waves. As mentioned above, this analysis may help highlight whether either of these events contained the trapped waves which are instrumental in convective initiation. To better visualize this, it is helpful to show what percent of the total covariance existed in the real and imaginary parts of the spectrum.

As one would expect, most of the propagating wave signatures are evident in the real part of the Cov(u,w). Since the real part is a proxy for momentum flux, if the majority of the signal is in the real part of the Cov(u,w), there must be momentum flux and subsequently, propagating waves. Times closest to the convection have most of the signal in the real part of the spectrum, from 23:30 to 00Z. These events have periods of about 9.5 minutes and 22 minutes respectively. In contrast, if

most of the Cov(u,w) signal exists in the imaginary part of the spectrum, there is little momentum flux taking place and we can infer that the waves are trapped. A trapped wave event is clearly evident from 21:30 to 23:00Z, with nearly 80% of the Cov(u,w) being represented by the imaginary part (Fig. 7). Again, the period corresponding to this event is approximately 16.7 minutes which falls within the range of periods expected for convectively generated gravity waves.

3. DISCUSSION

Low frequency gravity waves with periods on the order of storm timescale are difficult to accurately sample with traditional gravity wave measurement techniques. Measurements from a microwave profiling radiometer provide high temporal resolution of retrieved parameters which may help to identify both mode 1 and mode 2 low frequency signals. Care needs to be taken when selecting convective events for analysis, due to the masking effect caused by a leading stratiform cloud region of any low frequency signals.

Spectral analysis of 50 MHz wind profiler data has proven valuable in determining the presence of high frequency gravity wave activity in the troposphere from organized convection. While such data requires attention initially to remove any bad data, with the appropriate smoothing techniques one can extract The cross S-transform analysis meaningful signal. showed some particularly interesting results, indicating a trapped wave event in the forward environment with a period consistent with that of convectively generated gravity waves. While the trapped wave event can be inferred from the CST analysis, more information is needed to solidify our findings, such as additional stability information which can help identify trapping mechanisms. We are continuing to study observations to gain a more comprehensive picture of the high frequency/low frequency interaction seen in the models. and the role that interaction plays in convective initiation.

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