Further Discussion Of The Dynamical Processes That Contribute To The Spectrum Of Mesoscale Atmospheric Motions

In recent years much progress has been made in determining the spectrum of mesoscale atmospheric motions. The frequency spectra of vertical and horizontal velocities have been determined in the free atmosphere by means of the nearly continuous measurement of radial velocity by wind-profiling Doppler radar (Balsley and Carter, 1982; Gage and Nastrom, 1985; Ecklund et al., 1986). In addition, wind measurements by commercial aircraft collected during the NASA Global Atmospheric Sampling Program (GASP) have been analyzed to yield wavenumber spectra in the upper troposphere and lower atmosphere that cover scales ranging from a few km to 10,000 km (Nastrom and Gage, 1985).
FURTHER DISCUSSION OF THE DYNAMICAL PROCESSES THAT CONTRIBUTE TO THE SPECTRUM OF MESOSCALE ATMOSPHERIC MOTIONS

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1. INTRODUCTION

In recent years much progress has been made in determining the spectrum of mesoscale atmospheric motions. The frequency spectra of vertical and horizontal velocities have been determined in the free atmosphere by means of the nearly continuous measurement of radial velocity by wind-profiling Doppler radar (Balsley and Carter, 1982; Cage and Nastrom, 1985; Ecklund et al., 1986). In addition, wind measurements by commercial aircraft collected during the NASA Global Atmospheric Sampling Program (GASP) have been analyzed to yield wavenumber spectra in the upper troposphere and lower stratosphere that cover scales ranging from a few km to 10,000 km (Nastrom and Cage, 1985).

The synthesis of the observed atmospheric spectra into a dynamical framework has proceeded along several lines. Two conceptual models have been proposed to explain the nature of the spectra. The first is analogous to the Garrett-Munk spectrum of internal waves in the ocean. The second relies on a combination of the internal wave spectrum and a spectrum of quasi-horizontal motions presumably associated with the vorticity bearing mode of fluid motions. This vortical mode possesses vertical variation and is often referred to as quasi-two-dimensional or stratified turbulence. In the following sections we shall briefly review the current status of these two competing models of mesoscale atmospheric spectra and present some new results of an analysis of the dependence of frequency spectra of horizontal velocity upon background wind speed that may provide a basis for evaluating the relative contributions of waves and turbulence to the spectrum of horizontal motions in the atmosphere.

2. BACKGROUND

The idea that the spectrum of mesoscale atmospheric motions might be due to an incoherent spectrum of internal wave motions analogous to the Garrett-Munk spectrum in the ocean appears to have originated with the work of Dewan (1979) and VanZandt (1982). VanZandt examined the observed atmospheric spectra of horizontal motions and showed that it was possible to construct a universal model of the atmospheric spectrum in the spirit of Garrett-Munk that fit the atmospheric observations quite well. However, since little information was available at the time on the magnitude and shape of the spectrum of atmospheric vertical motions, the VanZandt model did not take them into account. Subsequently, as summarized in Ecklund et al. (1986), it now appears that a rather flat, nearly universal spectrum of vertical velocity exists in the atmosphere at least under light wind conditions. The possibility that this vertical velocity spectrum is nearly universal has been reinforced by recent results of the Flatland radar (Green et al., 1988) that show that in the absence of significant orography flat vertical velocity frequency spectra are obtained under a wide range of atmospheric conditions. However, the magnitude of this observed vertical velocity spectrum is not consistent with the VanZandt (1982) model spectrum as was pointed out by Cage and Nastrom (1985).

The original VanZandt model spectrum was normalized to fit the observed atmospheric horizontal velocity spectrum. If the observed vertical velocity spectrum is assumed to be an internal wave spectrum, it is possible to calculate the horizontal velocity spectrum of internal waves by employing the polarization relations and dispersion relation for internal waves. The spectrum of horizontal motions due to internal waves using this approach is shown in Fig. 1. Also shown in Fig. 1 are observed horizontal velocity spectra. In these examples, the observed horizontal velocity spectra contain more energy than the model spectrum at all frequencies. While this suggests that other processes besides internal waves may be responsible for the spectrum of horizontal motions, it must be kept in mind that up to this point no attempt has been made to account for Doppler shifting effects. Recently Scheffler and Liu (1986) and Fritts and VanZandt (1987) have been able to model the influence of mean wind speeds on internal wave spectra and their results show that the effect of Doppler shifting on atmospheric internal waves is not negligible.

The possibility that the observed atmospheric spectrum of horizontal motions may be dominated by processes other than internal waves was considered by Lilly (1983) and Cage and Nastrom (1985a, 1985b). These authors suggested that the horizontal velocity spectrum may be a manifestation of the vortical mode of fluid motions also known as stratified turbulence or quasi-two-dimensional turbulence. Lilly based his analysis on earlier work by Riley et al. (1981) that showed that at low Froude numbers it was possible through a scaling analysis to separate the equations of motion into...
Calculations and VaiZandt (1987) provide a means to quantify the possibility that the observed atmospheric velocity spectra contain contributions from waves and quasi-two-dimensional stratified turbulence has been considered by Gage and Nastrom (1985a, 1985b).

Both points of view discussed above accept the idea that the spectrum of vertical motions is largely determined by a spectrum of internal waves. Only in the importance attached to quasi-two-dimensional turbulence do the points of view differ. Doppler shifting effects may provide a way to differentiate waves and turbulence. The calculations of Scheffler and Liu (1986) and Fritts and VanZandt (1987) provide a means to quantify the Doppler shifting effect of a mean velocity on a spectrum of internal waves. The Taylor transformation can be used to relate frequency spectra of turbulence to the wave number spectra of atmospheric motions.

\[ \beta = \frac{U_m}{N} \]

where \( m_a \) is a characteristic vertical wavenumber, \( U \) is the mean wind speed, and \( N \) is the Brunt-Vaisala frequency. The influence of the mean wind on the spectrum of horizontal velocity for internal waves is illustrated in Fig. 2 which is taken from Fritts and VanZandt (1987). Figure 2 shows that qualitatively the influence of the mean wind is to broaden the spectral amplitude at the high frequency end of the spectrum and to decrease the spectral amplitude at the low frequency end of the spectrum. The net effect of the mean wind is to increase (make less negative) the spectral slope above -2 which is the slope of the model spectrum without Doppler shifting. Note that this change in spectral slope is in the sense required to fit the observed spectral slope in Fig. 1. Note also that only those waves with a component of their phase velocity in the direction of the mean wind are Doppler shifted.

\[ E(f) = 2\pi E(k)/U \]

where \( f = \frac{\mu k}{2\pi} \)

To determine the dependence of the wind speed, we adopt the model wavenumber spectrum contained in Fig. 3. This model wavenumber spectrum is a good approximation to the climatological GASP spectrum (Nastrom and Gage, 1985). Using Eqs. (2) and (3) we calculate the frequency spectra pertinent to various advection velocities as illustrated in Fig. 4. Note that unlike the wave spectra in Fig. 2, the turbulence spectra in Fig. 4 retain their original spectral slope. Their spectral magnitude increases uniformly at all frequencies with increasing advection velocity. Actually, over mountainous terrain, the GASP spectra are modified somewhat (Nastrom et al., 1987) and these modifications should be taken into account in a more complete analysis.

\[ \text{Fig. 1. Comparison of observed frequency spectra of horizontal motions with the frequency spectrum of horizontal buoyancy wave motions consistent with a model tropospheric vertical velocity spectrum.} \]

\[ \text{Fig. 2. Doppler shifting effect of a mean wind on a model buoyancy wave spectrum of horizontal velocity. (After Fritts and VanZandt, 1987.)} \]
Model Wavenumber Spectrum Based on GASP Spectra

![Model Wavenumber Spectrum](image)

**Fig. 3.** Model horizontal wavenumber spectrum of horizontal velocity based on GASP spectra.

Frequency Spectrum

- ○ 3 m s⁻¹
- ▲ 7 m s⁻¹
- + 13 m s⁻¹
- × 20 m s⁻¹

![Frequency Spectrum](image)

**Fig. 4.** Doppler shifted frequency spectra of horizontal velocity determined by Taylor transformation of the model wavenumber spectrum contained in Fig. 3.

5. **THE OBSERVED DEPENDENCE OF THE FREQUENCY SPECTRUM OF HORIZONTAL VELOCITY UPON WIND SPEED AT PLATTEVILLE, COLORADO**

The 50 MHz Doppler radar located at Platteville, Colorado, has been observing horizontal and vertical velocities routinely since 1981. For the purposes of the present paper accumulated data from 1981-1984 were analyzed to determine the dependence of the frequency spectra upon background wind speed. The frequency spectrum of the observed winds were calculated for 3 hour and 9 hour periods and data were stratified according to mean horizontal wind speed. Composite spectra were formed for each wind speed interval. Composite 3-hour spectra for the zonal wind are shown in Fig. 5. These spectra show a general increase in spectral amplitude with increasing wind speed. Spectral shape does not appear to be greatly affected by increasing mean winds over the range 2 to 20 m s⁻¹.

![Composite Spectra](image)

**Fig. 5.** Observed 3-hour frequency spectra of horizontal zonal velocity at Platteville, Colorado during summer months stratified by wind speed.

5. **COMPARISON OF THE OBSERVED DEPENDENCE OF THE HORIZONTAL VELOCITY SPECTRUM ON MEAN VELOCITY WITH THE WAVE AND TURBULENCE MODELS**

In this section we compare quantitatively the dependence of the observed frequency spectrum of horizontal velocity upon mean wind speed with the Doppler shifting effect discussed in Section 3. This is accomplished by determining the change in spectral amplitude with changing wind speed. Since we are concerned primarily with the relative magnitudes of the spectra, all changes in spectral amplitude are determined relative to the spectral amplitude of the non-Doppler shifted (or lowest wind speed) spectrum. Changes in the spectral amplitude are determined as a function of wind speed at several frequencies. The frequencies chosen for the comparison are the Brunt-Vaisala frequency N, a frequency equal to 0.1N, and a frequency equal to 0.01N. The observed frequency spectrum does not extend to low enough frequencies to compare with the wave and turbulence models at 0.01N but the changes in spectral amplitude for the models have been included here for completeness.

In order to determine the changes in spectral amplitude for the wave model it is necessary to assign a value to the characteristic
The wave and turbulence models employed here must be considered as approximate and the results shown are necessarily of a statistical nature. The observations are limited to a single location and may not be typical of other locations. For these reasons the results presented here must be regarded as preliminary.

7. REFERENCES


