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4.4 ADVANCES IN UNDERSTANDING THE GRAVITY WAVE SPECTRUM DURING MAP

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1. Introduction

Prior to MAP, virtually nothing was known about gravity wave spectra in the atmosphere. Fluctuations of atmospheric variables had been extensively observed during the 60s and 70s, but they had not been interpreted as being due to gravity waves. Weinstein et al. [1966] considered three processes that might cause the observed fluctuations: inertial oscillations, gravity waves, and paired vortices. They favored inertial oscillations and rejected gravity waves and paired vortices. Their analysis appears to have been tacitly accepted, since there was very little further discussion of the causes of the fluctuations until 1979.

In 1979 new or renewed interpretations were advanced. Dewan [1979] suggested that the observed fluctuations were due to a random superposition of gravity waves. Alternatively, Gage [1979] suggested that they were due to two-dimensional turbulence. The tension between these conflicting interpretations, the important new data generated during MAP, and the recognition that gravity waves play a critical role in the large-scale dynamics of the atmosphere have stimulated a great deal of work devoted to describing the fluctuations, usually in terms of power spectra, and to understanding their causes and effects.

The development of observational techniques has played a major role in these studies. Radar and lidar have been particularly important since they can measure atmospheric parameters continuously over large height ranges. Thus they permit the calculation of power spectra versus frequency from time series for the first time and the calculation of spectra versus vertical wave number, which previously could be obtained only from infrequent balloon or smoke trail data. The MST radar technique also has the unique capability of measuring the vertical velocity.

2. The Garrett and Munk Model Gravity Wave Spectrum

Oceanic internal fluctuations had been shown by Garrett and Munk [1972, 1975] to be due to a random superposition of gravity waves. Following Dewan's suggestion, VanZandt [1982] showed that the GM (1975) model also fits the atmospheric spectra. Their model for the energy spectrum can be written

$$F(\omega,m) + CE\omega^{-p}/(1 + m/m_*)^t \tag{1}$$

where ω is the frequency, m is the vertical wave number, C is a normalization constant, E is the energy per unit mass, and m_* is the characteristic vertical wave number or wave number bandwidth. Model spectra for horizontal velocity u, vertical velocity w, potential temperature θ, pressure, density, etc. versus ω , m, and horizontal wave number k can be obtained by use of the gravity wave dispersion and polarization relations in suitable integrals of (1).

The spectrum is defined by only for parameters: E, m_*, p, and t, which can be determined by fitting the model to two spectra, one versus ω and one versus k or m. VanZandt [1982] estimated these parameters by the fittings shown in Figures 1 and 2. Determination of the parameters using nonsimultaneous spectra was possible only because the parameters do not vary a great deal from place to place and time to time. The standard deviation of E over many observed spectra is found to be a factor of 2 or 3; m_*, which is the least well-determined parameter, appears to be constant within a factor $2^{1/2}$ at a given height, but it increases slowly

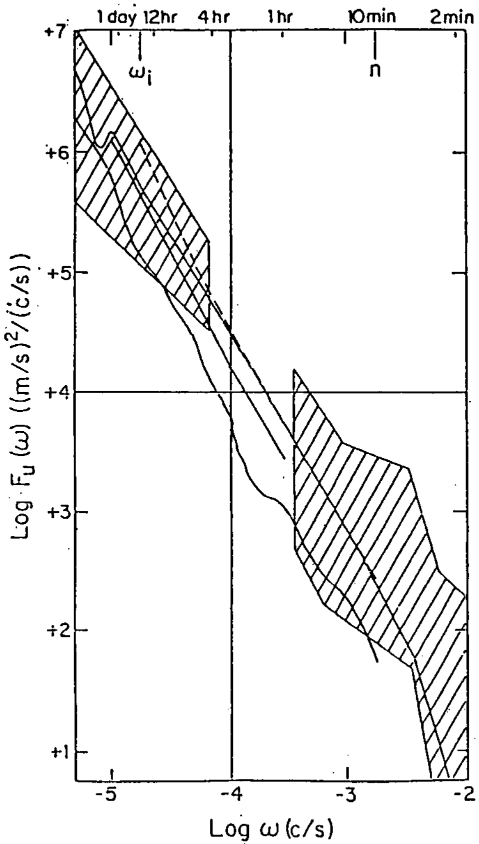

Figure 1. The GE model $F_{ul}(w)$ spectrum (dashed line) superimposed on observed spectra: upper, Vinnichenko [1970]; middle Balsley and Garello [1985]; lower, Balsley and Carter [1982].

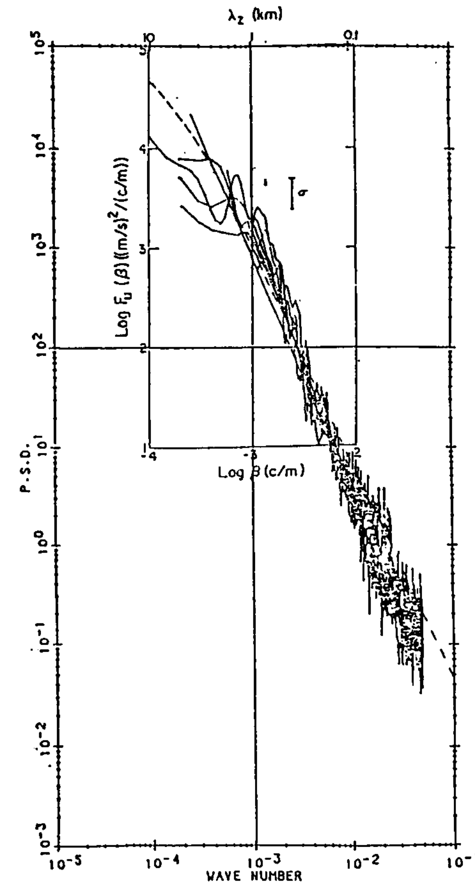

Figure 2. The GW model F_{ul} spectrum (dashed line) superimposed on observed spectra: solid straight line, Daniels [1971]; raw spectra, Dewan et al. [1984].

with height; $p \approx 5/3 \pm 1/6$; and m_* lies between 2.5 and 3, with theory (discussed later) suggesting a value closer to 3.

In each figure the model spectrum is the dashed curve. In Figure 1 the parameters were determined by fitting to the line that runs through the hatched areas. The model vertical wave number spectrum in Figure 2 was fitted to the observed spectrum indicated by the solid straight line in the inner box, which was derived from balloon data in the troposphere. It also fits the spectra reported by Dewan et al. [1984] from smoke-trail data in the middle stratosphere. The similarity of the five smoke-trail spectra, which were taken at three quite different locations, illustrates the constancy of vertical wave number spectra.

Once the four parameters have been determined, the model predicts all of the other spectra, so that the model can be tested by comparing the predicted spectra with observations. Two examples of such tests are shown in Figures 3 and 4, which compare predicted model spectra with observed spectra of temperature versus vertical wave number (Figure 3) and of horizontal velocity and potential temperature versus horizontal wave number (Figure 4). In Figure 4 the model fits the observed spectra extraordinarily well for wavelengths shorter than about 200 km, even following the curvature at wavelengths shorter than about 10 km. It must be emphasized that the model spectra are defined solely by the parameters determined in Figures 1 and 2; they are not adjusted at all to fit the observed spectra. Comparisons such as these strongly support the concept that the observed fluctuations are due to a random superposition of gravity waves.

The GM model has been extended to apply to radial velocities such as those measured by an oblique radar or lidar [Scheffler and Liu, 1985; VanZandt, 1985] and to take into account Doppler shifting of frequency spectra by the background wind [Scheffler and Liu, 1986; Fritts and VanZandt, 1987].

The GM model is thus a good description of the spectrum of the mean gravity wave field. While description of the mean state is important, departures from the mean are in some respects more critical. In particular, the mean state provides little or no information about the sources, propagation, and sinks of gravity wave energy. Moreover, the model does not explain the values of the parameters that are observed, or why the range of each parameter is limited. Publication of the GM model in 1972 stimulated research to try to explain the observed spectral shapes and amplitudes in terms of nonlinear interactions in the wave field. In spite of a great deal of work, reviewed by Müller et al. [1986], the problem is still not solved satisfactorily.

Saturated Vertical Wave Number Spectra

In the atmosphere, however, there has been some progress toward explaining the value of t and the variation of m_* with altitude in terms of saturation of the gravity wave spectrum. Dewan and Good [1986] and Smith et al. [1987] argued that because the amplitude of the spectrum increases with altitude, the large wave number part of the spectrum should be saturated. This process is quite important because in regions where gravity waves are saturated and dissipate, horizontal momentum is transferred from the gravity wave field to the mean flow. This acceleration has important effects on the global dynamics of the atmosphere [Houghton, 1978; Lindzen, 1981].

According to Smith et al. [1987] and Fritts et al. [1988], the saturated velocity and temperature spectrum are approximately

$$F_u{}^s(m) = N^2/6m^3 \text{ and } F_T{}^s(m) = N^4/10m^3 \qquad (2)$$

In Figure 5 these spectra are plotted as dashed lines with a value of N appropriate to the lower stratosphere. They agree very well with observed lower stratospheric spectra, shown as solid

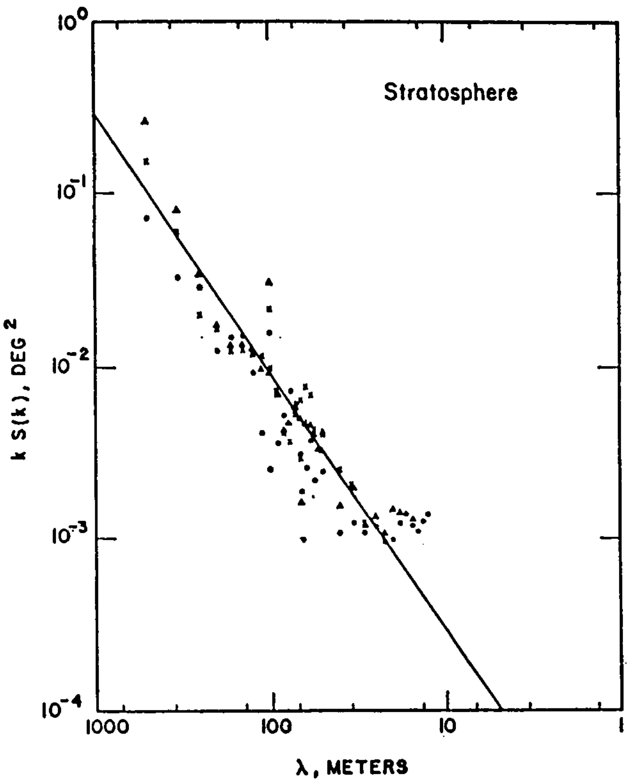

Figure 3. The GW model $F_O(m)$ spectrum superimposed on spectra observed by Mantis [1972].

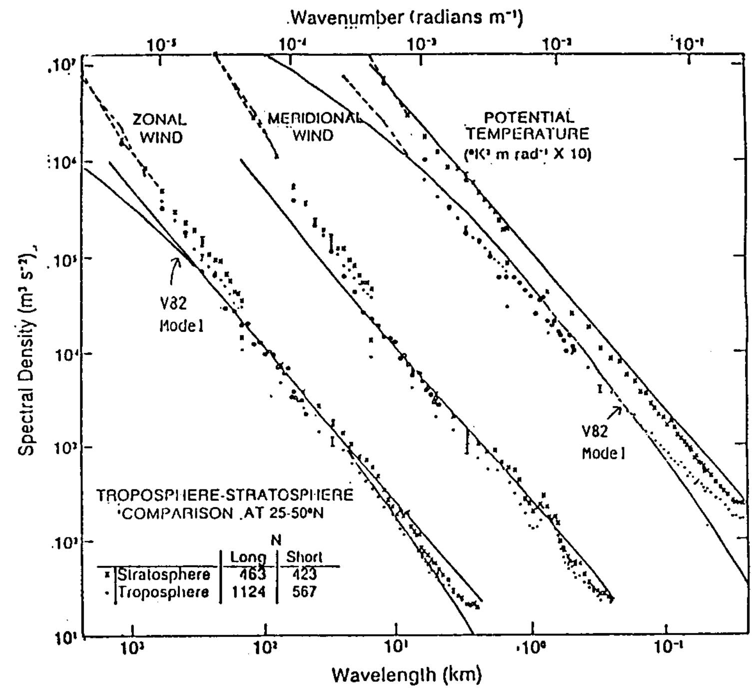

Figure 4. Comparison between observed spectra of horizontal wind and potential temperature versus k [from Nastrom and Gage, 1985] and the GM model [from VanZandt, 1982].

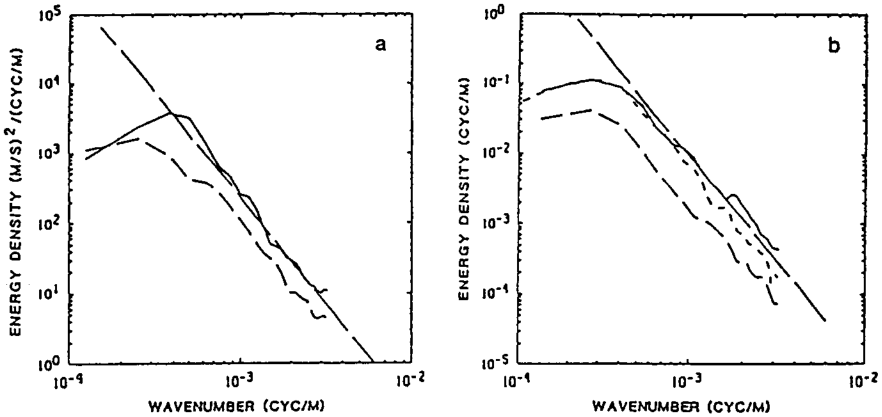

Figure 5. Comparison of the model saturated spectra (dashed lines) with observed spectra of (a) horizontal velocity and (b) normalized temperature. The observed spectra are (– –) 5-12.5 km, (——) 12.5-20.5 km, and (----) 20.5-30 km. [After Fritts et al., 1988].

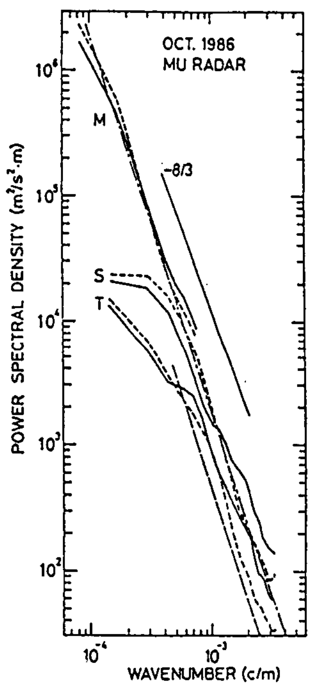

Figure 6. Comparison of the model saturated spectrum of horizontal velocity with spectra in the troposphere (T), stratosphere (S), and mesosphere (M) observed essentially simultaneously by the MU radar. The zonal spectra are indicated by solid curves and the meridional spectra (which are freer from contamination) by dashed curves. [After Tsuda et al., 1989].

curves. The saturated spectra for the troposphere are smaller because the tropospheric value of N is smaller.

In Figure 6, $F_u^s(m)$ is compared with spectra from the troposphere (T), stratosphere (S), and mesosphere (M) observed essentially simultaneously by the MU radar. The zonal spectra are indicated by solid curves and the meridional, by dashed curves. The tropospheric and stratospheric models are the dashed and dot-dashed lines, respectively. Again, the agreement is very good, particularly with the meridional spectra. The zonal spectra are contaminated by an instrumental effect at large wave number. The decrease of m_* with increasing altitude is discussed by Smith et al.

Vertical Velocity

Several studies of the spectra of vertical velocity have been made, taking advantage of the unique capability of the MST radar technique. Under light wind conditions (<5 m/s) the frequency spectra are rather flat, as shown by the curves labeled "QUIET" in Figure 7. The thin spectra are from the ALPEX radars in the delta of the Rhone river in southern France and the thick spectra are from the Flatland radar in Illinois. These spectra are reasonably consistent with the GM model, which predicts a slope of $-p + 2 \simeq + 1/3$. But under high wind conditions (> 20 m/s), labeled "ACTIVE", the ALPEX spectra increase in amplitude and become much steeper, approaching a slope of $-5/3$, while the Flatland spectra increase only slightly and become slightly flatter. We attribute the drastic change in the ALPEX spectra, and at other spectra taken near rough terrain, to contamination of the vertical velocities by mountain waves.

Figure 8 compares the Flatland spectra, stratified by wind speed, with model Doppler-shifted spectra. The agreement between the observed and model spectra as the mean wind changes strongly suggests that the observed spectra are almost entirely due to gravity waves.

The following graphs show that it may be possible to measure synoptic-scale vertical velocities using the MST radar technique with a radar located in very flat terrain. This is very important since, although synoptic-scale vertical velocities play a critical role in atmospheric dynamics, it has not been possible to measure them directly.

Figure 9 is a mean spectrum extending out to a period of 45 h plotted on an area-preserving graph. In the lower left-hand corner is plotted an estimate of the mean spectral density due to synoptic-scale motions, assuming that the synoptic-scale variance is about 12 $(cm/s)^2$ and that the spectral density per unit of log frequency is uniform between 7 days and 5 hours. The fact that the Flatland spectrum lies at or below the estimated synoptic-scale spectrum suggests that a radar in very flat terrain may be able to measure the synoptic-scale velocity. Of course, such a measurement would be quite impossible at ALPEX or at any other station near rough terrain.

Two-Dimensional Turbulence

It was mentioned earlier that Gage [1979] suggested that the observed fluctuations are primarily due to 2 DT. But it is impossible to assess how much of the fluctuations are due to 2 DT because the theory makes only very few predictions, and the observations that can be compared with these predictions are also consistent with the gravity wave interpretation as shown above.

Because the role of 2 DT cannot be assessed by comparison with observations, almost all of the studies attempting to show the importance of 2 DT have proceeded by first assuming that the motions must be either 2 DT or gravity waves and they trying to show that the fluctuations cannot be due to gravity waves. These arguments have been flawed by the use of inappropriate data or questionable assumptions.

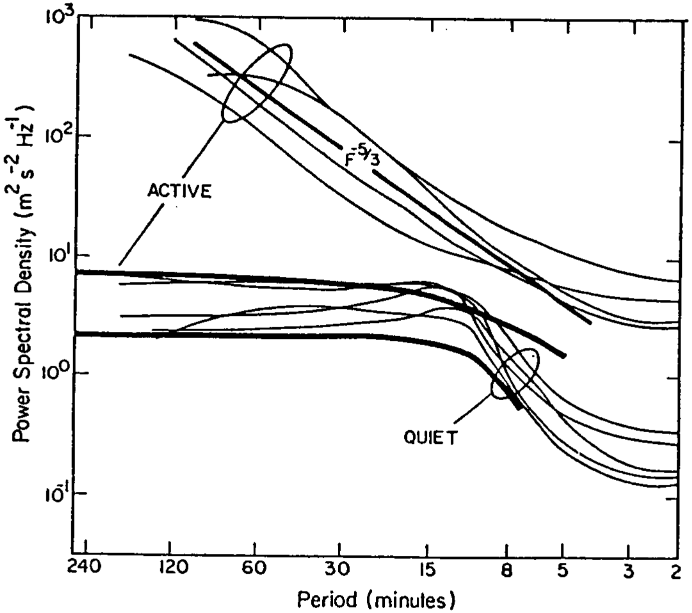

Figure 7. Frequency spectra of vertical velocity fluctuations. The ALPEX spectra from Ecklund et al. [1985] are the average of four 750 km range gates centered from 3.85 to 6.10 km and the Flatland spectra are from the 5.2 km range gate.

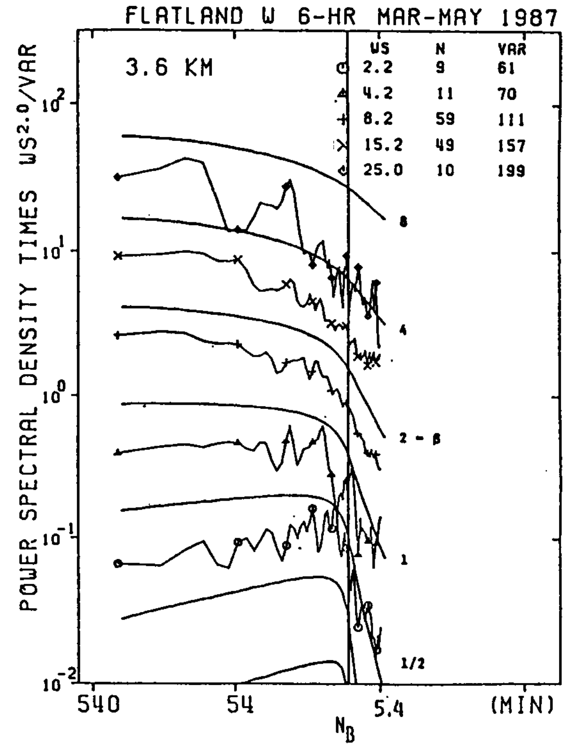

Figure 8. Comparison between frequency spectra of vertical velocity fluctuations at Flatland, stratified by background wind speed WS, with model Doppler-shifted spectra. $\beta = WS/C_*$ where C_* is the characteristic horizontal phase speed.

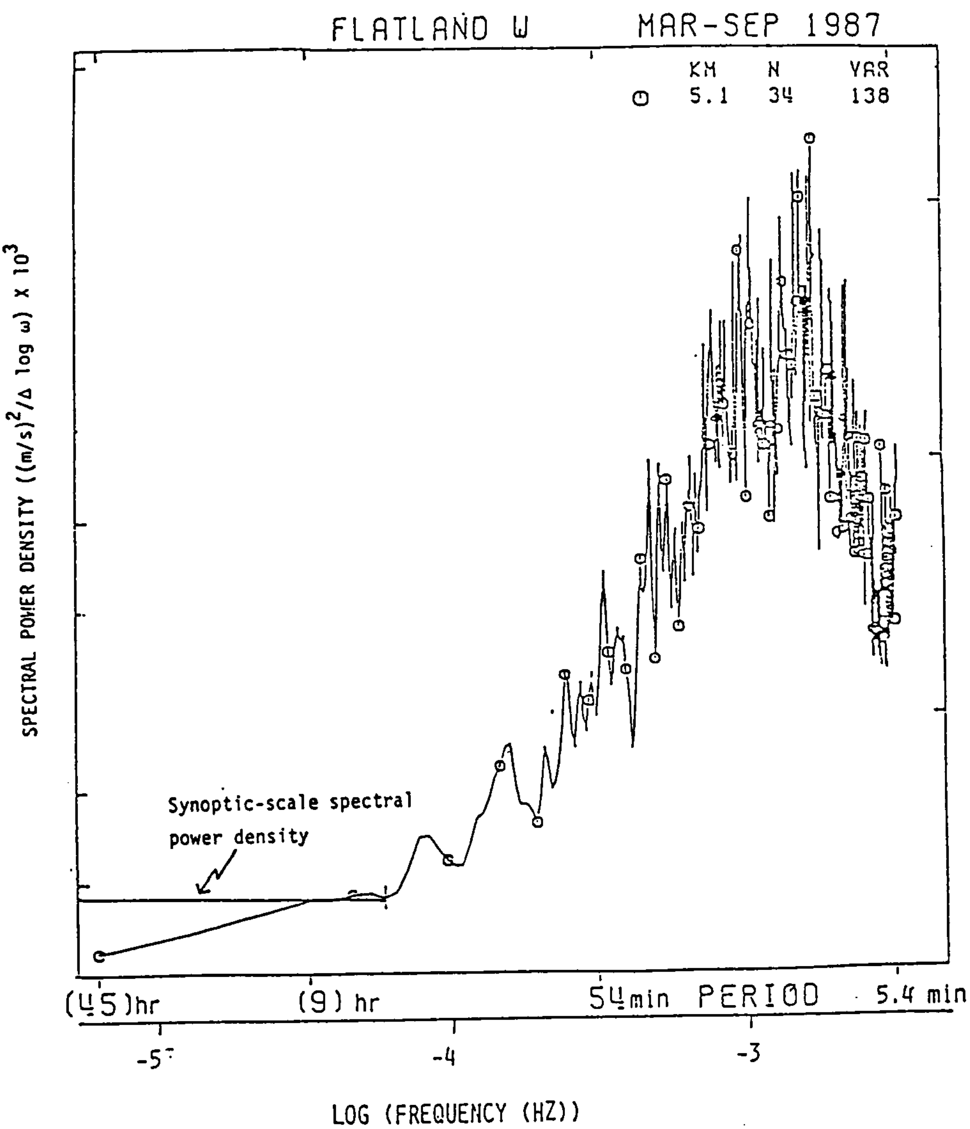

Figure 9. Mean frequency spectrum of vertical velocity at Flatland extending to 45 h compared with an estimate of the mean spectral density due to synoptic-scale vertical motions.

Conclusions

1. The observed fluctuations and power spectra in the free atmosphere are mostly if not entirely due to a superposition of gravity waves, which can be modeled by the GM model.

2. There is no evidence that 2 DT makes a significant contribution to the observed fluctuations. In any case, the agreement between observations and the GM model shows that the 2 DT contribution must be relatively small.

3. Spectra versus vertical wave number are saturated at large wave number, with theory and observations indicating that $t \approx 3$.

4. Vertical velocity fluctuations and spectra measured near rough terrain are strongly contaminated by mountain waves. But over very flat terrain the spectra are dominated by gravity waves at periods shorter than about 6 hours and apparently by synoptic-scale velocities at periods longer than 6 hours. Thus it may be possible to study synoptic-scale vertical velocities using radars located in very flat terrain.

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