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A Preliminary Climatology of the Spectrum of Vertical Velocity Observed by Clear-Air Doppler Radar

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ABSTRACT

Multiheight time series of atmospheric vertical velocities in the troposphere and lower stratosphere observed by clear-air Doppler radar are presented at various locations around the world. Frequency spectra of vertical velocities determined from these data sets are compared with the objective of developing a preliminary climatology. We emphasize the nearly universal shape and magnitude of spectra observed during low-wind conditions. These spectra are quite flat for frequencies between the buoyancy and inertial frequencies, and they closely resemble the internal wave spectra observed in the ocean. Spectra observed under strong wind conditions, on the other hand, are greatly enhanced in magnitude, approaching the $f^{-5/3}$ spectral slope observed for the spectrum of horizontal motions. Finally, spectra determined from both quiet and active periods at Poker Flat, Alaska, possess spectral slopes and amplitudes intermediate to those spectra determined solely from quiet or active periods at other locations.

1. Introduction

Recent advances in clear-air Doppler radar probing of the atmosphere have made possible for the first time routine continuous monitoring of atmospheric winds over an altitude range including most of the troposphere and lower stratosphere (Gage and Balsley, 1978; Balsley and Gage, 1982). These radars have the capability of observing vertical as well as horizontal motions (e.g., see Nastrom and Gage, 1984; Nastrom et al., 1985). While several studies have been published concerning the temporal spectra of horizontal winds observed by these radars (Balsley and Carter, 1982; Larsen et al., 1982; Gage and Nastrom, 1985), relatively little has appeared in the open literature concerning the observed vertical velocity spectra.

It has been hypothesized by Dewan (1979) and VanZandt (1982) that the mesoscale spectra of horizontal and vertical atmospheric motions are dominated by internal gravity waves. Under idealized conditions of no background wind or ocean current, internal gravity waves in the atmosphere and in the ocean range over periods from the Brunt–Väisälä (B–V) period ($\tau_B \sim 5$–20 min) to the inertial period (~18 h at 42° lat). More generally, the waves may extend beyond these limits because of the influence of Doppler shifting. Waves with periods close to the B–V period are mostly comprised of vertical motions, while waves with periods close to the inertial period are mostly quasi-horizontal.

The concept of a background spectrum of internal waves is not new but has been hypothesized by oceanographers to explain the spectrum of motions in the ocean ranging over the frequencies occupied by internal waves. Garrett and Munk (1972, 1975) advanced a kinematic model for internal wave spectra in the ocean; the model assumes an isotropic spectrum of waves. Unlike turbulence, internal wave spectra are weakly nonlinear and the frequency and wavenumber spectra are related through the internal wave dispersion relation. While the model does not take into account Doppler-shifting effects, after a decade of testing, the model spectra have been found to fit available observations in the ocean rather well (Olbers, 1983).

If the hypothesis of Dewan and VanZandt is correct, the atmospheric spectra should be analogous to the Garrett–Munk spectrum in the ocean. Since the relationship between the shapes and intensities of the spectra of horizontal and vertical motions are known in the context of the wave theory, the consistency of the vertical velocity spectrum with the known horizontal velocity spectrum becomes a fairly crucial test of the concept that the mesoscale atmospheric spectra are solely the result of a spectrum of internal gravity waves. Alternatively, Gage (1979) and Lilly (1983) have argued that the mesoscale spectrum of horizontal wind could be explained by a reverse-cascading quasi-two-dimensional turbulence. Clearly, it is essential to know the vertical velocity spectrum to understand the underlying mechanisms responsible for mesoscale atmospheric motions. These issues as well as the possible role of Doppler-shifting in the atmosphere are discussed in more detail by Gage and Nastrom (1985).

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In this paper we use observations from several clear-air Doppler radars situated at a variety of different locations to determine the general character of the frequency spectrum of vertical velocities in the clear atmosphere. Several of these radars have operated more or less continuously during the past few years. For example, the Poker Flat MST (mesosphere, stratosphere, troposphere) radar (Balsley et al., 1980) has been in continuous operation since 1979. The Platteville radar, which is part of the Colorado wind-profiling network (Strauch et al., 1984), has been operated continuously since mid-1981 and has been used, for example, in a comparison study with the Sunset radar (Ecklund et al., 1982). The Ponape radar in the central Equatorial Pacific (Balsley et al., 1984) was installed in April 1984 and has been observing vertical velocities almost continuously since then. In addition, several research campaigns have been conducted using clear-air Doppler radars for brief periods (e.g., Ecklund et al., 1985). Thus, there is now enough data available from widely separated geographical locations to establish at least a preliminary climatology of the frequency spectrum of atmospheric vertical velocities.

2. Vertical velocity measurement by clear-air Doppler radar

Although clear-air Doppler radars operate over a range of frequencies spanning VHF (30–300 MHz; λ = 10–1 m) and UHF (300–3000 MHz; λ = 1–0.1 m), all of the observations reported here are by VHF Doppler radar operating at 50 MHz (λ = 6 m). These radars have large antennas comprised of phased arrays of dipole elements and typically operate unattended at low power. They are thus ideal for collecting routine continuous observations which can be used for climatological studies. The VHF Doppler radars obtain their echoes from the weak backscatter due to inhomogeneities in radio refractive index in the optically clear air. Specifically, the radars are sensitive to the inhomogeneities on the scale of half the radar wavelength (3 m at 50 MHz), and the Doppler shift of the radar echo provides a measure of the radial component of velocity (i.e., the velocity component along the direction of the radar beam). The vertical velocities reported here were all obtained using vertically directed radar beams. Typically, Doppler spectra are obtained from radar observations averaged over about one minute. The Doppler spectra are then processed to extract the mean Doppler shift, as described in Carter et al. (1980).

3. General features of vertical velocities measured by clear-air Doppler radar

The locations of the radars used in this study are shown on the world map in Fig. 1. The Platteville radar and the radars used in the ALPEX campaign are located at midlatitudes. The Poker Flat MST radar is located in Alaska near Fairbanks (65°N, 148°W) and the Ponape radar is located in the western tropical Pacific (7°N, 158°E). For later reference, it should be noted that all of the radars are located in or near rough terrain.

Several studies of vertical wind variability have already been made using some of these radars. Röttger (1981) reported the first vertical velocity spectra obtained using clear-air Doppler radar. Ecklund et al. (1981) described the general features of multiheight time series of vertical velocities observed at Poker Flat. Their observations, reproduced in Fig. 2, show these features quite clearly. The most striking features evident in the 34-day record are the recurring episodes of active periods of enhanced vertical velocity variability. A detailed statistical analysis of the vertical velocity variability at Poker Flat was made by Nastrom and Gage (1984). These authors showed that the vertical velocities were distributed lognormally and tentatively concluded that the active periods and quiet periods could be attributed to two different processes with distinct statistical character. On the basis of these observed features, it appears the active periods are limited episodes of enhanced vertical velocity variance which are superposed on a more or less uniform background of reduced vertical velocity variance.

Ecklund et al. (1982) examined the vertical velocity variability observed at Platteville, Colorado, located in the lee of the Colorado Rockies. The same general feature of alternating periods of active and quiet vertical velocity variability are evident in Fig. 3, which shows a multiheight time series of vertical velocities observed at Platteville. Also evident in Fig. 3 are periods of upward and downward motions persisting for many hours. These motions are presumably related to lee wave activity.

Figures 4 and 5 show similar records of multiheight time series of vertical velocities observed in France during ALPEX (Ecklund et al., 1985) and more recently at Ponape (Balsley et al., 1984). While Fig. 4 shows very active periods associated with the strong mistral winds blowing down the Rhone Valley, the active periods observed at Ponape are less intense, of shorter duration and confined to tropospheric altitudes. In evaluating the climatological significance of these alternating periods of quiet and active vertical velocities it must be borne in mind that all these observations are from or close to rough terrain. There is a strong possibility that the active periods shown in Figs. 2–5 are the result of waves generated by flow over rough terrain. Supporting this conclusion is the excellent correlation between vertical wind variability observed at Platteville and 500-mb zonal wind shown in Fig. 6 (Ecklund et al., 1982). Active periods were confined to those times when tropospheric winds were from the west (i.e., from over the mountains). In marked contrast, quiet periods occurred whenever the tropospheric wind was either weak or from another direction. Results

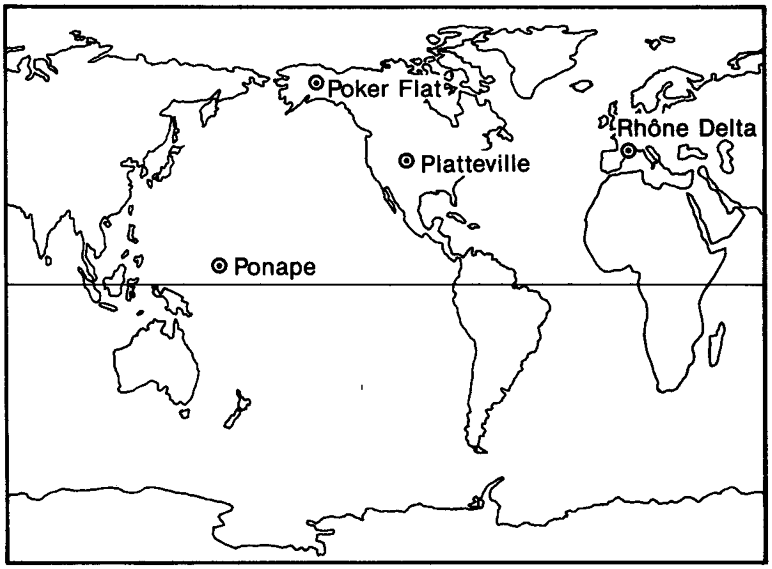

FIG. 1. World map showing locations of radars used in this study.

of a correlation analysis indicate that the vertical velocity variability at all heights is most closely correlated with the zonal wind speed from the midtroposphere at 700–500 mb. The magnitude of this correlation is close to 0.7.

The occurrence of periods of enhanced vertical-wind variability is of more than academic interest. As pointed out by Nastrom et al. (1985), the possibility of direct measurement of synoptic- and subsynoptic-scale mean vertical motion depends critically on the level of background vertical wind variability. There is little or no hope of measuring the very small synoptic-scale vertical motion during the active periods when vertical velocity variability is high. However, during quiet conditions when vertical velocity variability is low, case studies reported in Nastrom et al. (1985) show good agreement between radar-observed vertical motion averaged over nine hours and synoptic-scale vertical motion deduced from NMC analyses.

In sections 4–6 we focus attention on the spectrum of vertical motion observed during quiet periods. This approach is adopted here because we believe that the quiet period spectra represent a nearly universal background upon which the active periods are superposed locally from time to time.

4. The quiet-time vertical velocity spectrum

In this section we present and compare the spectrum of vertical motion observed under quiet (weak wind) conditions at the four widely separated locations shown on the map in Fig. 1. Here, we define quiet wind con-

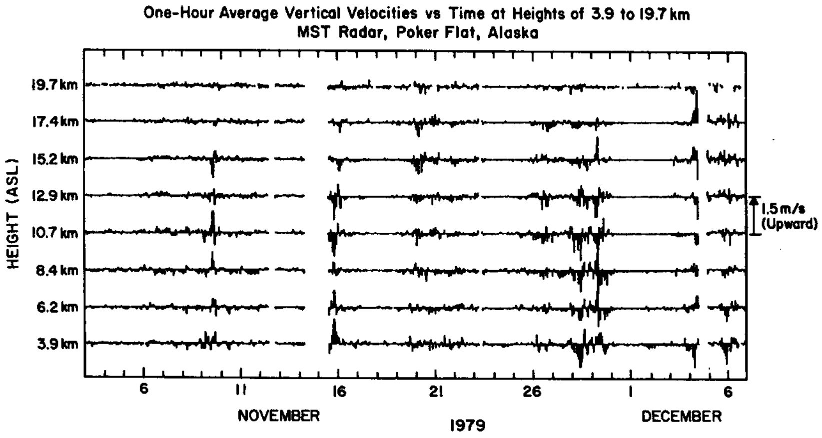

FIG. 2. Multiheight time series of vertical velocities observed at Poker Flat (Ecklund et al., 1981).

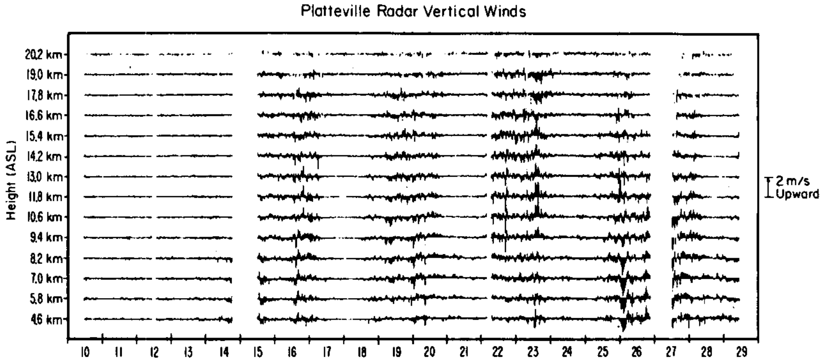

FIG. 3. As in Fig. 2 but for Platteville, Colorado (Ecklund et al., 1982).

ditions as pertaining to wind profiles with speeds less than about 10 m s^{-1} throughout the troposphere.

Typical quiet-time spectra are shown in Fig. 7. These spectra are from tropospheric and stratospheric altitudes determined from data taken during the ALPEX campaign described in Ecklund et al. (1985). Note that the spectra are quite flat over the range of periods greater than the B–V period. (These periods in both the troposphere and stratosphere are indicated in this figure by the vertical arrows.) Simultaneous spectra observed nearby with a broader beamwidth antenna appear very similar. All these spectra exhibit a peak at periods slightly longer than the B–V period and fall-off rapidly at periods less than the B–V period. This characteristic is expected for a spectrum of internal waves and is very similar to that observed in the ocean (Eriksen, 1978). Note that even the relationship of spectral amplitude and stability is roughly as anticipated for a spectrum of internal waves.

According to the internal wave theory, the amplitude of the vertical velocity spectrum should vary directly with the B–V period (e.g., see Olbers, 1983). Consistent with this expectation, the B–V period in the troposphere (in Fig. 7) exceeds the B–V period in the stratosphere by about a factor of 2, while the amplitude of the tropospheric vertical velocity spectrum is about 1.5 times the amplitude of the stratospheric vertical velocity spectrum.

A quantitative comparison between quiet-time vertical velocity spectra for Platteville, Rhone Delta (France), Poker Flat and Ponape is shown in Fig. 8. In all cases, the spectral shape for periods greater than 20 min or so are reasonably flat. Also, the spectral amplitudes are nearly comparable, with a variation of only a factor of 2 or 3 about the mean amplitude. Note, however, that the Platteville spectrum, which has the largest amplitude, shows no pronounced peak at the B–V frequency. This may be due to the fact that background wind speeds were not as small as for some of the other spectra shown in Fig. 8.

5. Comparison with other observations

Since direct measurements of vertical velocity in the free atmosphere are very sparse, we cannot compare the vertical velocity spectra determined here with spectra obtained from other techniques. Nevertheless, there is a very close relationship between the vertical velocity spectrum and the variance of vertical velocity $\overline{w^2}$, and there are enough in situ measurements of vertical velocity variance even in the free atmosphere to make some comparisons.

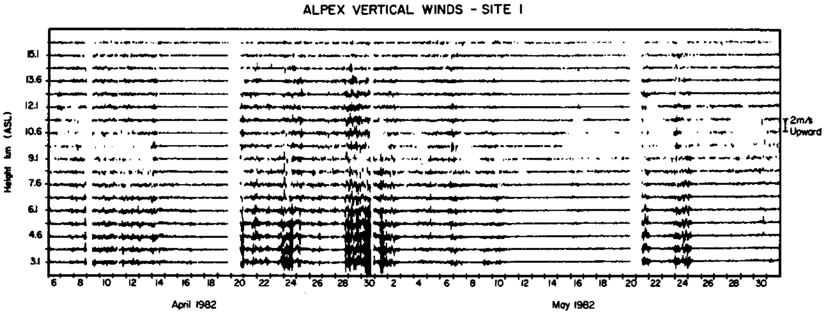

FIG. 4. Multiheight time series of vertical velocities observed at one of three radars operated in the Rhone Delta, France, during ALPEX (Ecklund et al., 1985).

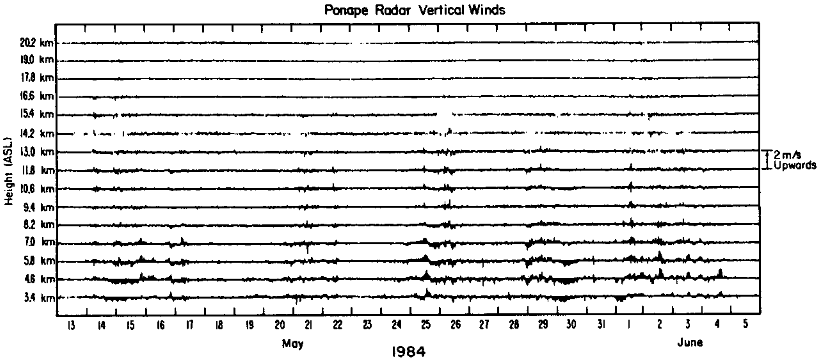

FIG. 5. As in Fig. 2 but for Ponape.

The magnitude of $\overline{w^2}$ is given by the integral of the power spectrum of vertical velocity $\Phi_{ww}(f)$ integrated over all frequencies in the spectrum. That is,

$$\overline{w^2} = \int_0^\infty \Phi_{ww}(f)df. \tag{1}$$

For the quiet-time vertical velocity spectrum presented in the last section, Φ_{ww} can be approximated by

$$\Phi_{ww}(f) = \begin{cases} A_{ww}(f_B) & \text{for } f_B > f > f_i \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

where A_{ww} is the amplitude of the vertical velocity spectrum which is here assumed to be independent of f, and f_i and f_B are the inertial and B–V frequencies, respectively.

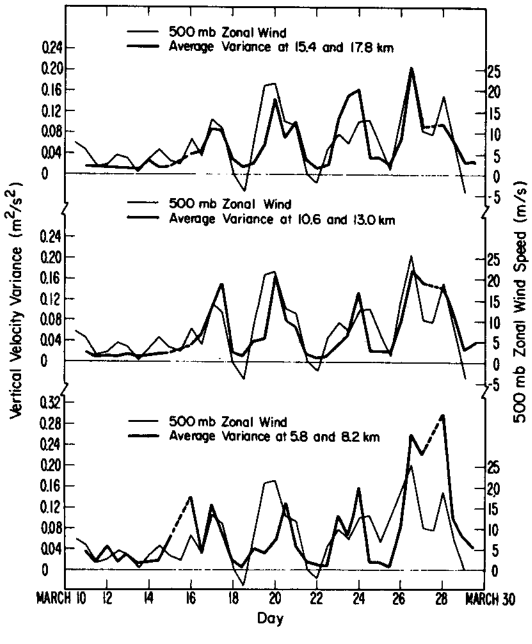

FIG. 6. Comparison of vertical wind variability observed at Platteville with the magnitude of 500-mb zonal wind (Ecklund et al., 1982).

Substitution of $\Phi_{ww}(f)$ in the form of Eq. (2) into Eq. (1) leads to

$$\overline{w^2} = A_{ww}(f_B - f_i) \approx A_{ww}f_B, \tag{3}$$

which simply relates the vertical velocity variance to the spectral amplitude and the B–V frequency. Note that for a spectrum of internal waves scaled by f_B in accordance with the Garrett–Munk theory (Olbers, 1983), $A_{ww} \propto 1/f_B$ so that $\overline{w^2}$ should be independent of f_B. For the vertical velocity spectra of Fig. 8, however, scaling by f_B does not bring the spectra into appreciably better agreement. In Fig. 8, A_{ww} ranges from 1.7 to 8.6 $\times 10^4$ cm^2 s^{-1} while $\overline{w^2}$ (from Eq. 3) ranges from 22 to 80 cm^2 s^{-2}. Taking into account the spectral peak near the B–V period, this estimate of $\overline{w^2}$ needs to be raised by a factor of 2 or so. Accordingly, we conclude that the range of $\overline{w^2}$ consistent with the spectra of Fig. 3 is approximately 50–200 cm^2 s^{-2}.

We have compared the above estimates of $\overline{w^2}$ with more direct radar determinations of vertical velocity variability and found them to be in essential agreement. For example, a climatology of $\overline{w^2}$ prepared for Poker Flat by Nastrom and Gage (1984) shows a background value close to 100 cm^2 s^{-2} with occasional episodes of much higher values ($>10^3$ cm^2 s^{-2}) during active periods. A similar pattern was observed at Platteville (Ecklund et al., 1982) as shown in Fig. 4.

The radar measurements of $\overline{w^2}$ agree with, and significantly expand upon, the sparse measurements available above the boundary layer from in situ measurements. Aircraft and pilot balloon measurements of $\overline{w^2}$ summarized by Roll (1965) show that the mean value above the planetary boundary layer (at 1–2 km) is between 100 and 400 cm^2 s^{-2} and decreases slightly with increasing altitude. Roll also notes that $\overline{w^2}$ shows little dependence on averaging time for periods over 10–15 min. This feature can now be understood in terms of the shape of the vertical velocity spectrum; i.e., for a flat spectrum the contribution to the total variance at any period is inversely proportional to the period. Thus, the greatest contribution to the total variance comes from the vicinity of the B–V period

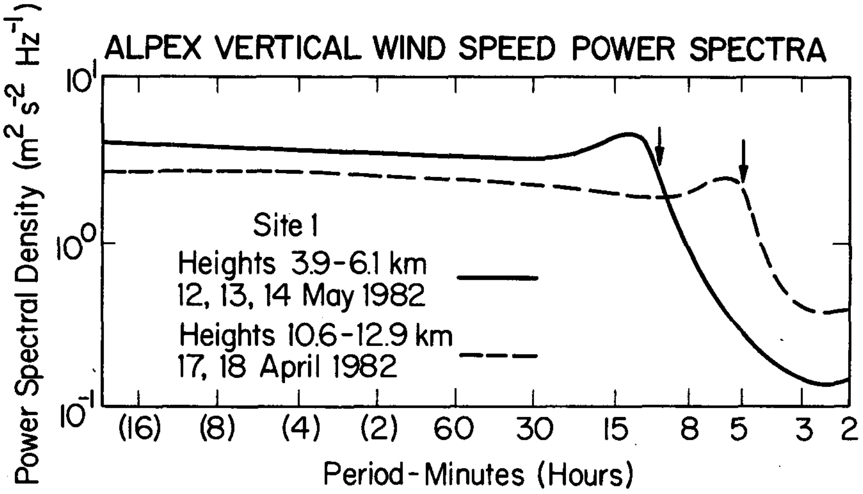

FIG. 7. Vertical velocity spectra observed at tropospheric and stratospheric altitudes at the Rhone Delta during low-wind conditions (Ecklund et al., 1985).

(i.e., from periods close to 10 min). Nastrom (1980) presented values of $\overline{w^2}$ for 38 constant-density balloon flights near 1-km altitude, and the mean value was close to 400 cm² s⁻². Allowing for a possible decrease in $\overline{w^2}$ above 1-km altitude and the increase in $\overline{w^2}$ anticipated for more general conditions (discussed below), the quiet-time, higher-altitude radar results 50–200 cm² s⁻²) are remarkably consistent with the balloon data. Thus, we conclude that the amplitude of the radar spectra are consistent with balloon and aircraft data.

6. General spectra of vertical velocity

Up to this point, we have focused attention on the vertical velocity spectrum obtained under quiet-wind conditions. We believe that this spectrum is due to a nearly universal spectrum of internal waves. Next, we briefly consider the vertical velocity spectra found when we separate active from quiet periods in the analysis of vertical velocity variance.

Spectra shown in Fig. 9 illustrate the extreme contrast in vertical velocity spectra observed during ALPEX (Ecklund et al., 1985) between quiet and active periods. Here, the active periods correspond to times of strong low-level winds associated with the mistral. Note that during these active periods the spectral power is greatly enhanced at periods longer than the B–V period. In fact, the spectral slope approaches $f^{-5/3}$, i.e., the same slope as observed for the frequency spectrum

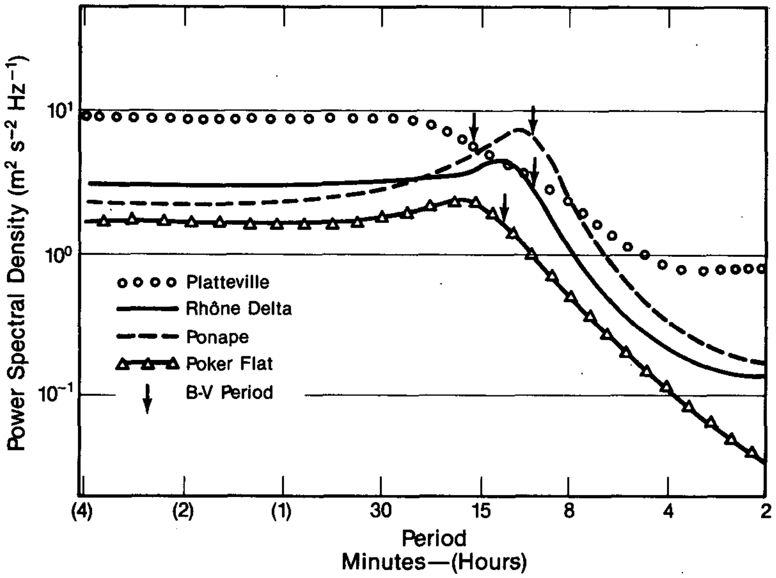

FIG. 8. Intercomparison of quiet-time vertical velocity spectra observed at Poker Flat, Alaska; Platteville, Colorado; Rhone Delta, France; and Ponape.

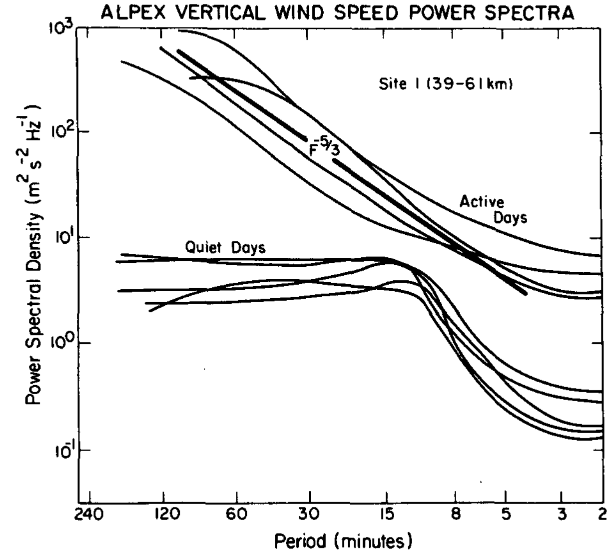

FIG. 9. Comparison of quiet and active vertical velocity spectra observed at the Rhone Delta, France (Ecklund et al., 1985).

of horizontal velocity reported by Balsley and Carter (1982). Gage and Nastrom (1985) have pointed out that in the atmosphere there is much more energy in quasi-horizontal motions than in vertical motions. Accordingly, any disturbance, such as mountain lee waves, that can cause isentropic surfaces to depart appreciably from the horizontal will also cause otherwise horizontal motions to possess an appreciable vertical component. This physical picture, then, involves the distortion of quasi-horizontal motions which would be expected to closely follow isentropic surfaces. Note also that Doppler-shifting effects would tend to spread energy from the spectral peak seen in the quiet spectra near the B–V to higher and lower frequencies.

If active and quiet periods are considered together, or if the vertical velocity spectrum is formed for general conditions at stations that experience an alternation of active with quiet periods, the climatological vertical velocity spectrum will be intermediate to the quiet and active vertical velocity spectra. For example, Fig. 10 shows such a spectrum as it pertains to general conditions at Poker Flat. Note that the spectral slope is now closer to f^{-1} for periods larger than the B–V period. Although the plotted curves in Fig. 10 extend only to 16-h periods, we have computed the spectra over periods out to three days, and the slope remains nearly constant at the longer periods. For sites located far from significant terrain variability where topography is not a factor, we anticipate that active periods are confined to specific episodes of convection or jet stream instabilities. Under these circumstances, we would anticipate that a typical vertical velocity spectrum would look more like the quiet spectra which were presented in section 4. Unfortunately, no radars currently operate in such flat terrain, but data from existing radars support this idea since active periods are almost always associated with strong winds flowing over rough terrain.

7. Summary and conclusions

In this paper we have examined the spectra of vertical velocities obtained by time series analysis of vertical velocity data taken by clear-air Doppler radar at four widely separated geographical locations. We have considered primarily the quiet-time spectrum (observed when background winds are weak), and our observations indicate that this spectrum is nearly universal and closely resembles (in shape) the vertical velocity spectrum associated with the Garrett–Munk model spectrum in the ocean. We therefore tentatively conclude that this quiet-time spectrum is the atmospheric analog of the ocean internal wave spectrum.

We have compared the amplitude of the quiet-time spectrum with the vertical velocity variance determined by balloon and aircraft. While the in situ observations are very sparse, the variances obtained independently by these techniques are quite consistent with the variances observed by Doppler radar. This comparison with balloon and aircraft data provides an independent

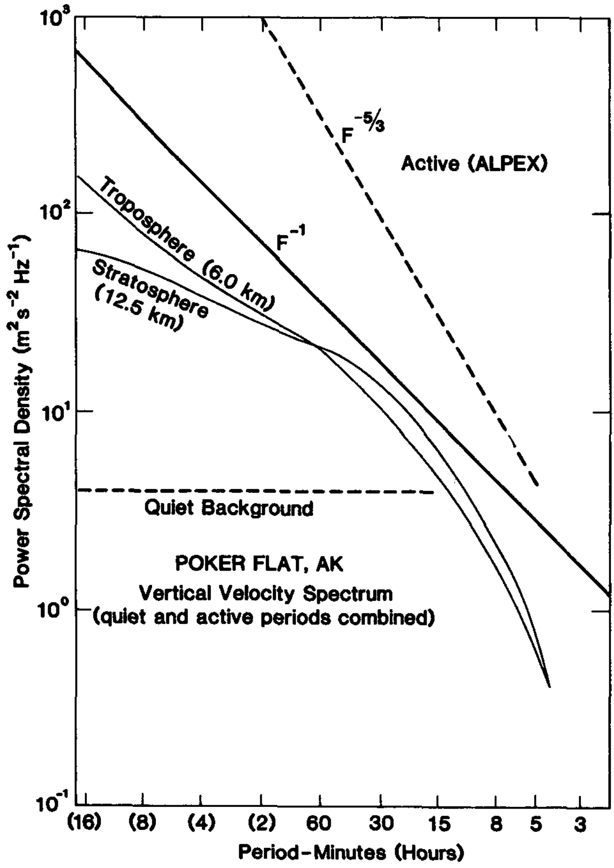

FIG. 10. Vertical velocity spectrum observed at Poker Flat under general conditions encompassing both active and quiet conditions.

check on the amplitude but not the shape of the radar-observed spectra. It would be highly desirable in future experiments to take in situ measurements of vertical motions in conjunction with radar observations to further clarify the nature of the radar-observed motions.

We have also examined the vertical velocity spectra obtained under more general conditions. Under extreme circumstances of strong winds and intense lee-wave activity, the spectra show a dramatic change of slope approaching the $f^{-5/3}$ spectral slope observed for the spectrum of horizontal motions. Spectra obtained from data comprised of both quiet and active periods at Poker Flat are intermediate in amplitude and slope to spectra obtained under quiet or active conditions.

Finally, it should be noted that the vertical velocity spectrum can be compared for consistency with internal wave models which assume that the horizontal velocity spectrum is also due to waves. This comparison has recently been made elsewhere (Gage and Nastrom, 1985), and the result shows a significant discrepancy between the observed horizontal and vertical velocity spectra and current internal wave models advanced to explain the mesoscale spectrum of atmospheric motions (VanZandt, 1982; Scheffler and Liu, 1984). It goes beyond the scope of the present paper to speculate further on the dynamics of the mesoscale spectrum of atmospheric motions, but we reemphasize that the quiet-time spectrum of vertical motions does seem to unambiguously represent a nearly universal spectrum of internal waves.

These results provide a first look at the climatology of the atmospheric vertical-velocity spectrum. With the continued use of new radars in various locations throughout the world, we can anticipate that much more data will be available in a very few years to develop a more complete climatology.

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