3.4A ON THE MEASUREMENT OF VERTICAL VELOCITY BY MST RADAR

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ABSTRACT

An overview is presented of the measurement of atmospheric vertical motion utilizing the MST radar technique. Vertical motion in the atmosphere is briefly discussed as a function of scale. Vertical velocity measurement by MST radars is then considered from within the context of the expected magnitudes to be observed. Examples are drawn from published vertical velocity observations.

INTRODUCTION

MST radar measurements of atmospheric vertical motion have been available for about 5 years. The first measurements were associated with case studies and invariably of short duration. More recent observations are nearly continuous over long periods and provide a basis for evaluating the climatology of the vertical wind.

In view of the large amount of vertical wind data available for analysis, surprisingly little has been published. Nevertheless, the vertical wind data constitutes a valuable resource. I believe that part of the reason that more has not been done with the vertical winds lies in the lack of suitable techniques for verification. Also, since the (specular) scattering mechanism thought to be responsible for much of the vertical echoes seems to differ from the turbulent scattering mechanism which is thought to cause the off vertical echoes, one may reasonably question whether the observed vertical velocities are an accurate measurement of vertical air motion. Furthermore, routine direct vertical wind measurements have never been available from any source. It is therefore very difficult to form any independent judgment of the reasonableness of the observations.

In this paper I shall consider the meaning and possible significance of the vertical wind measurement within the context of current knowledge of the magnitudes of atmospheric vertical motion at different scales.

THE MAGNITUDE OF ATMOSPHERIC VERTICAL MOTION AS A FUNCTION OF SCALE

The magnitude of atmospheric vertical motion varies greatly with scale. The magnitude of the large-scale vertical motion is very small and has been determined by inference rather than by direct observation. Small-scale vertical motion on the other hand has been measured directly by several methods.

Estimates of mean vertical velocities associated with the general circulation of the atmosphere are given by the analysis of NEWELL et al. (1972). The largest vertical velocities averaged over a season are on the order of a few millimeters per second. These values occur in the equatorial zone and are associated with the ascending branch of the Hadley cell. They decrease considerably in magnitude in the lower stratosphere. Of course, larger vertical velocities would be anticipated higher in the middle atmosphere.

On the synoptic scale, vertical velocities show considerable variability. The dynamics of large-scale vertical motion is discussed by FLEAGLE (1958). Diverse methods for calculating large-scale vertical velocities are discussed in many papers (PANOFSKY, 1946; FLEAGLE, 1958; O'BRIEN, 1970; KUNG, 1972; STUART, 1974; SMITH and LIN, 1978; and PEDDER, 1981).

Qualitatively, it is easy to think of large-scale vertical motion as a consequence of nearly horizontal motion on isentropic surfaces. Isentropic surfaces are surfaces of constant potential temperature. Since parcels of air in adiabatic motion conserve potential temperature, it is reasonable to anticipate motion along isentropic surfaces. The consequences for vertical motion are clear when one considers the fact that (in the Northern Hemisphere) isentropic surfaces generally slope upwards from south to north. Northward motion is generally ascending and often associated with clouds and precipitation due to adiabatic cooling (PANOFSKY, 1946). In contrast, southward motion is typically descending and free of clouds. DANIELSEN (1961) pointed out the significance of isentropic analysis for trajectory calculations. He gave an example of a twelve-hour isentropic trajectory over the U.S. from northwest to southeast which implied a -7.4 cm s^{-1} average vertical velocity. KUNG (1972) presented an analysis of the synoptic scale vertical motion field in the troposphere over North America. Typical vertical velocities were on the order of 1 cm s^{-1} with extreme values about an order of magnitude larger. Large-scale vertical motions have been analyzed in the stratosphere (MILLER, 1970) and found to be in the same range at 2 mb (43 km).

Several studies have shown larger synoptic scale vertical velocities in the vicinity of jet streams and severe weather. WILSON (1976) analyzed 3-hr soundings made during NASA's Atmospheric Variability Experiment (AVE) and found extreme values of vertical motion of about 25 cm s^{-1} associated with severe convective storms. In an earlier study of vertical velocities associated with jet streams, ENDLICH (1953) concluded that values of 10 cm s^{-1} are common and that extreme values of the order of 25 cm s^{-1} are possible.

Clearly, the magnitude and variability of atmospheric vertical motions can be expected to increase with decreasing spatial and temporal scale. This is especially true on the mesoscale where disturbances of the smallest scale can possess large vertical velocities. While the mesoscale is not routinely observed, special studies have been made to determine the magnitude of mesoscale vertical motions (HARDMAN et al., 1972; TUCKER, 1973). FANKHAUSER (1974) has analyzed data collected from a special mesoscale sounding network used in Oklahoma by the National Severe Storms Laboratory (NSSL). His analysis revealed a systematic pattern of tropospheric vertical motion associated with a squall line. Maximum vertical velocities were on the order of 1 ms^{-1}. Vertical velocities have also been reported from a mesoscale analysis of BOMEX data by SMITH et al. (1975). They were found to be as large as .5 ms^{-1} in an active mesoscale disturbance.

On the cloud scale vertical velocities have been measured directly by aircraft, radar and balloons. Aircraft measurement of vertical velocity is discussed by LENSCHOW (1976) and LAWSON (1980). LeMONE and ZIPSER (1980) report vertical velocities measured by aircraft during GATE on the order of 5 ms^{-1}. They present statistical distributions of vertical velocities which show great variability. Vertical motions have also been deduced from ascent rate variations of rising Jimspheres tracked by radar (DeMANDEL and KRIVO, 1971). By subtracting out buoyancy and drag variations, estimates were made of vertical air motion. Vertical velocities on the order of .5 ms^{-1} were reported during ascent through clear skies. Vertical velocities on the order of 1 ms^{-1} have been obtained by precise tracking of constant level balloons (GAGE and JASPERSON, 1976). In convective storms vertical motions as high as 10 ms^{-1} have been observed by Doppler radar (BATTAN, 1973).

A BRIEF SURVEY OF VERTICAL VELOCITY MEASUREMENT BY MST RADAR

It should be clear from the material presented in the previous section that the entire spectrum of atmospheric vertical velocities is not well observed. It should also be clear that the magnitude of vertical motion decreases with increasing scale so that large-scale atmospheric motions are quasi-horizontal. It is only on the smallest scale that vertical velocities have been directly measurable and these have never been routinely available in the past.

Since MST radars measure the radial component of motion, the principle of measurement of vertical velocity is the same as for horizontal velocity. The most straightforward way to measure vertical velocity is to direct the antenna beam vertically. Since horizontal velocities are typically so much larger than vertical velocities, care must be taken that the antenna is directed truly vertically; otherwise, the measured velocity will be contaminated by a small component of the horizontal wind.

Another method for obtaining vertical velocity is from VAD analysis (PETERSON and BALSLEY, 1979; RABIN and ZRNIC', 1980). To employ this method the radar antenna must be capable of making a complete azimuth scan for fixed zenith angle. The horizontal velocity is determined by fitting a sinusoid to the radial velocity over the azimuth scan. The amplitude yields horizontal wind speed, the phase gives horizontal wind direction and any offset of the sinusoid about zero determines the vertical velocity. A third method is to perform an elevation scan. By this method radial velocity is plotted as a function of zenith angle and the vertical velocity is then determined by the intercept of the radial velocity at zero zenith angle. Vertical velocities from all three methods have been determined using the Chatanika radar (PETERSON and BALSLEY, 1979). The profiles of vertical velocity are reproduced in Figure 1 and show a reasonable consistency, especially at the lower heights where the vertical velocity is largest.

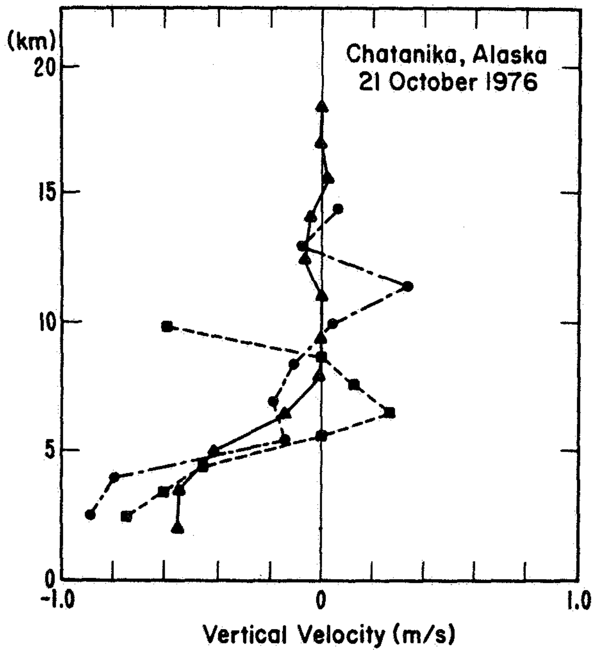

Figure 1. Comparison of the vertical component of wind velocity obtained by three different methods. (After PETERSON and BALSLEY, 1970.) [■...■ AZSCAN data, ● ... ● ELSCAN data, ▲ ... ▲ Zenith data]

Most MST radars do not have the capability of scanning and consequently the antenna must be directed at the zenith to measure vertical velocities. Several case studies have been made of vertical velocities observed in this manner. GREEN et al. (1978) observed the vertical wind associated with the passage of a strong southerly jet stream over the Sunset radar. They reported upward vertical motion as high as .5 ms^{-1} in the vicinity of the tropopause. GAGE et al. (1978) and ROTTGER (1980a) report vertical motion associated with convective storms. They found complicated patterns of updrafts and downdrafts with vertical velocities of several ms^{-1}.

The vertical velocities associated with a jet stream and upper level frontal zone were reported by LARSEN and ROTTGER (1982, 1983). The reflectivity and vertical velocities are reproduced in Figure 2. Upward vertical motion of about .5 ms^{-1} was found on the warm side of the front in the vicinity of the jet stream core. Downward motion of equal magnitude was found on the cold side of the front through most of the troposphere. Note the structure in the vertical velocity field. With some smoothing these velocities would reduce to the magnitude of synoptic scale vertical velocities.

Continuous measurements of vertical velocities are now available using MST radar. The longest uninterrupted data records are from the Poker Flat MST radar. A 34-day record of hourly-averaged vertical winds at Poker Flat is reproduced in Figure 3 (ECKLUND et al., 1981). This figure shows that the magnitude of the vertical wind varies greatly from day to day with occasional active periods disrupting a relatively quiet background. A sample of vertical velocities for a quiet period is given in Figure 4 and a sample of vertical velocities for an active period is shown in Figure 5. The accompanying 500 mb maps show that the active period is associated with the strong winds found in baroclinic zones. The correlation of vertical wind variability with wind speed has been verified in a recent climatological study by NASTROM and GAGE (1983).

The large magnitude and extreme variability of the vertical wind observed by MST radar has been attributed to internal gravity waves (or buoyancy waves). An example of a wave-like disturbance observed by the Poker Flat MST radar is reproduced in Figure 6 (GAGE et al., 1981). No apparent variation of phase with altitude was observed during this wave event suggesting that a trapped mode was observed.

Other MST vertical wind observations can be found in ROTTGER (1980c, 1981), FUKAO et al. (1978) and ECKLUND et al. (1982, 1983). In all cases the magnitude of observed vertical velocities are in reasonable agreement with the magnitudes of vertical velocities observed under similar circumstances using other techniques. However, no direct verification by independent means has yet been reported.

Vertical velocities have also been measured at mesospheric altitudes. Quasi-vertical motions showing gravity wave activity have been reported by WOODMAN and GUILLEN (1974) and by MILLER et al. (1978). More recently, BALSLEY and RIDDLE (1983) have analyzed the mean vertical motion observed at Poker Flat over several years. The mean wind is downward during the summer which suggests that upward motion in the summer mesosphere is confined poleward of 65°N.

THE ACCURACY OF VERTICAL WIND MEASUREMENT BY MST RADARS

As mentioned above, direct vertical wind measurement is a new commodity in meteorology. As a consequence, it is difficult to form an independent judgment concerning the validity of the MST radar vertical velocities. In marked contrast horizontal velocities determined from the Doppler shift due to turbulent scattering have been compared to balloon and aircraft derived velocities. While a few outstanding problems can compromise the validity of the

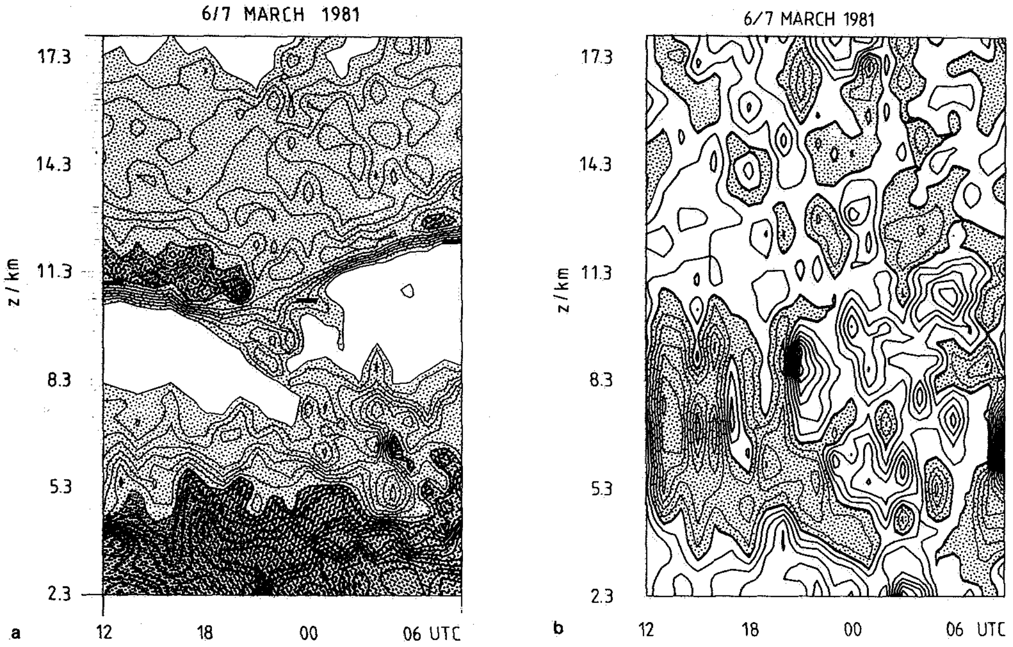

Figure 2. Observations of the SOUSY radar. a. Reflectivity contour plot. Difference between contour lines is 2 dB. Intensity of shading corresponds to intensity of echoes. b. Contour plot of vertical echoes. Shading indicates downward velocity. The interval between contours is 7.5 cm s^{-1}. (After LARSEN and ROTTGER, 1982.)

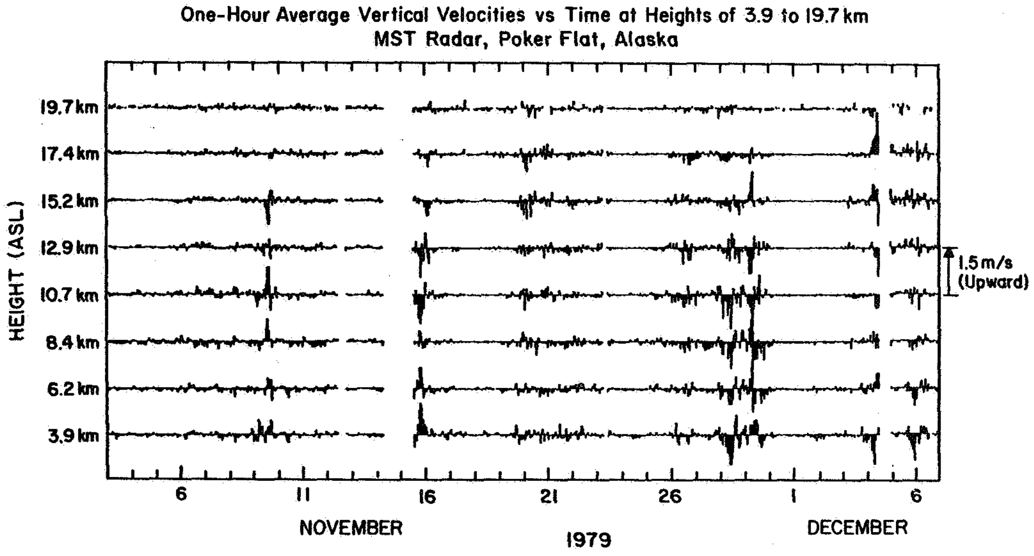

Figure 3. 34-day record of hourly averaged vertical wind velocites at heights of 3.9 - 19.7 km as observed by the Poker Flat MST radar. (After ECKLUND et al., 1981.)

horizontal winds, they are generally in excellent agreement with winds obtained by other accepted techniques.

Two features make the validity of vertical winds difficult to evaluate. First, the magnitude of vertical winds is much smaller than the magnitude of horizontal winds. Second, at least at lower VHF, MST radars obtain their echoes at vertical incidence from a quasi-specular scatter mechanism. Thus, the fact that horizontal winds are accurately measured cannot be used without qualification to justify the validity of the vertical wind measurement.

Local vertical winds observed by MST radars vary greatly but are usually less than 1 ms^{-1}. Because mean vertical motions are very small, it is appropriate and advantageous when measuring vertical velocity to reduce the limits of maximum unambiguous velocity to a few ms^{-1}. Doing this greatly

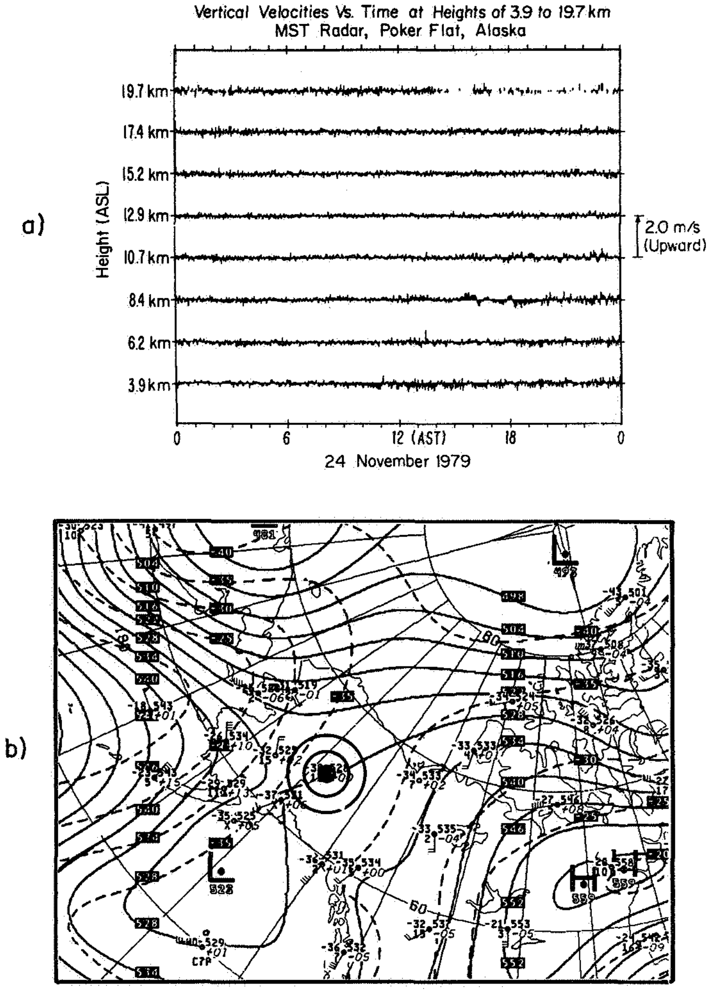

Figure 4. a. Vertical velocities observed by the Poker Flat MST radar on a quiet day (24 November 1979). b. The 500 mb analysis map for the quiet day. (After ECKLUND et al., 1981.)

improves the resolution of the vertical velocity measurement. For example, if $4\ ms^{-1}$ is used as a maximum unambiguous velocity and 256 points are used in an FFT, then vertical velocities as small as $3\ cm\ s^{-1}$ should be resolvable in individual spectra. Averaging, of course, further reduces the magnitude of vertical motion that can be resolved.

GAGE et al. (1981) considered the measurement of vertical velocity in relation to scattering mechanisms in an analysis of a wave event observed by the Poker Flat MST radar. The wave event as a time series of vertical velocity is shown in Figure 6. A comparison of the time series of velocities with the time series of received power and spectral width at 10.7 km is contained in Figure 7. The spectra reproduced in Figure 8 show that the observed spectral shape changed dramatically with the phase of the wave disturbance. Only when the vertical velocity was close to zero did the spectra truly appear specular. When the

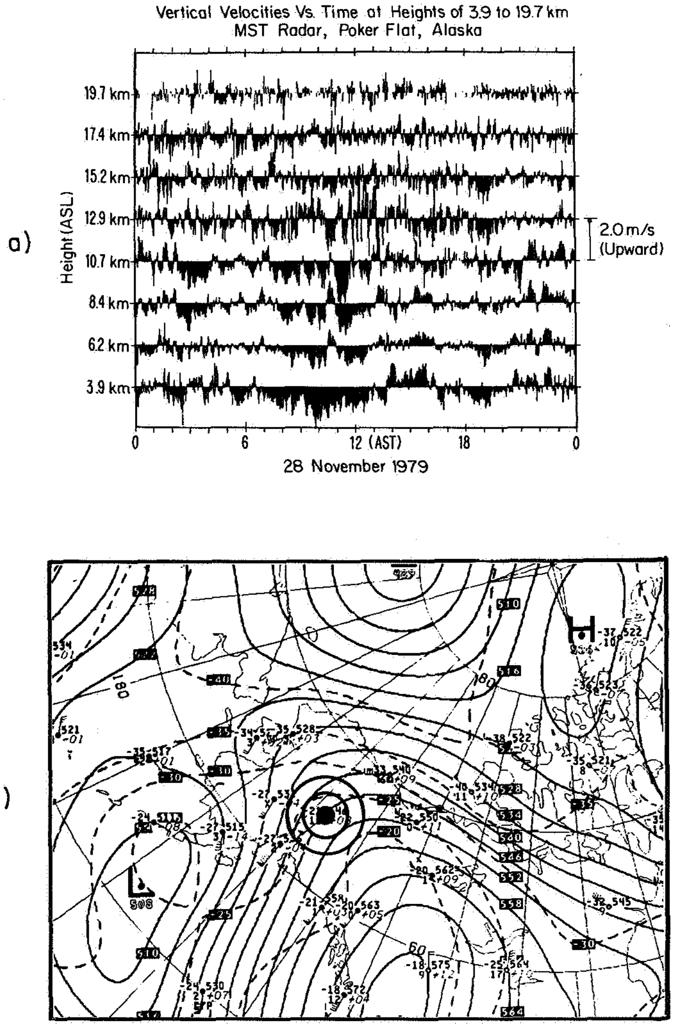

Figure 5. a. Vertical velocities observed by the Poker Flat MST radar on an active day (28 November 1979). b. The 500 mb analysis map for the active day. (After ECKLUND et al., 1981.)

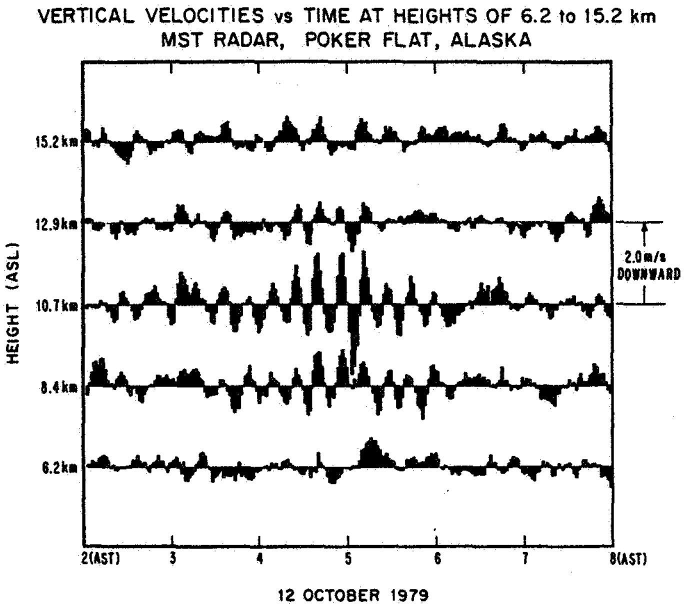

Figure 6. Vertical velocities observed from 6.2 km to 15.2 km for 6 hours on 12 October 1979. (After GAGE et al., 1981.)

vertical velocity departed significantly from zero, the spectral shape broadened and the magnitude dropped sharply. Thus, there is some evidence to suggest that the larger vertical velocities are a result of turbulent scattering and should therefore be valid.

There has been some concern that MST measured vertical velocities may not be valid under certain circumstances. ROTTGER (1980b) raised the concern that tilting of reflecting layers contributing to diffuse reflection could adversely bias the mean vertical velocities deduced from MST observations. Another related concern (ROTTGER, 1981) arises when a VHF radar determines the vertical velocity from a slightly tilted layer. The sloping layer can effectively tilt the incident beam slightly off-vertical and, as a consequence, a small component of the horizontal velocity would contaminate the vertical velocity measurement. In evaluating this concern it should be borne in mind that atmospheric motions are not strictly two-dimensional. Thus, a large-scale vertical velocity component can be anticipated even for an antenna beam directed strictly vertically. Whether tilting effects are a practical concern for the measurement of vertical velocities observed by MST radars needs to be evaluated more fully. It should be clear, however, that UHF radars should not experience these problems. The practical importance of these effects could be determined by careful comparisons of vertical velocity measurements obtained simultaneously at UHF and at lower VHF. Indeed, preliminary comparisons of vertical velocities measured by the Chatanika radar and the Poker Flat radar show close agreement (WATKINS and JAYAWEERA, 1983). Comparitive vertical velocity measurements with Doppler lidar should also be pursued.

CONCLUDING REMARKS

In this overview I have attempted to evaluate MST radar measurements of vertical velocities in the context of the magnitudes of vertical motion pertaining to varying scales of atmospheric motion. While no definitive conclusions can be made on the validity of MST vertical velocity measurement,

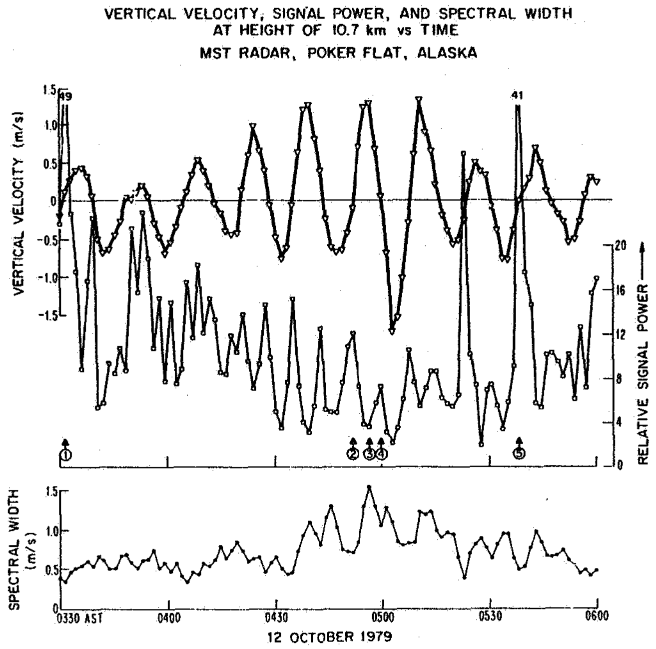

Figure 7. Time series of vertical velocity signal power, and spectral width observed during the wave event of 12 October 1979. The circled numbers refer to the spectra shown in Figure 8. Positive velocity values are downward (after GAGE et al., 1981.)

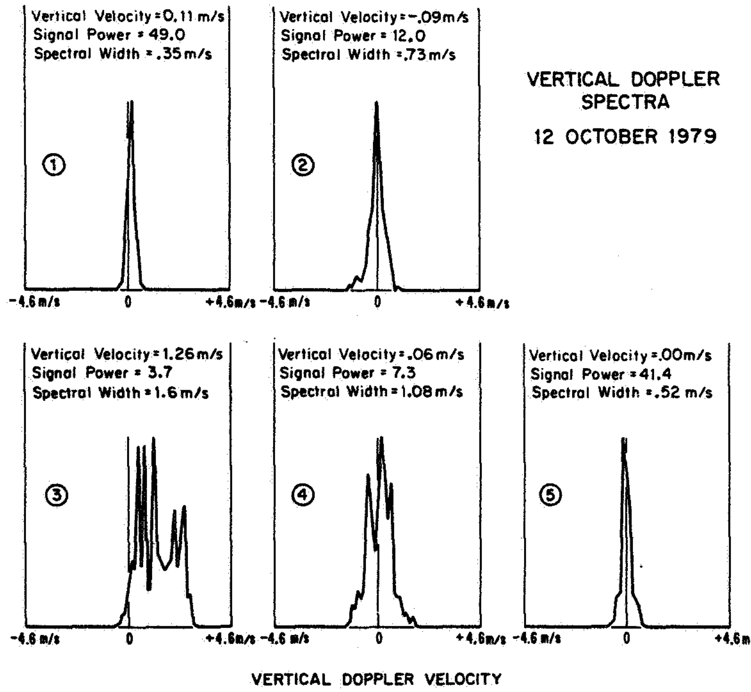

Figure 8. Doppler spectra observed at various stages of the wave event of 12 October 1979 (after GAGE et al., 1981).

observations to date are consistent with the magnitudes of vertical motion obtained by other methods. While some uncertainty remains due to the specular nature of lower VHF echoes at vertical incidence, there are indications that layer tilting effects will not limit the usefulness of MST vertical velocity measurements in practice. Remaining unresolved is the issue of whether synoptic scale vertical motions are measurable.

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