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VHF AND UHF DOPPLER RADARS AS TOOLS FOR SYNOPTIC RESEARCH

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M. F. Larsen and J. Röttger

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Abstract

Applications of VHF and UHF Doppler radars to research in synoptic meteorology are reviewed. We find that these radars show great potential for studies of large scales, but the area of research where the instruments really excel is in studying the interaction between the synoptic scale and the mesoscale. Several examples of results in both these areas are presented. Finally, the potential for operational use of the radar systems is discussed.

1. Introduction

Sensitive VHF and UHF Doppler radars are providing a powerful new tool for investigations of the dynamics of the atmosphere at small scales typically associated with gravity waves and 3-dimensional turbulence. VHF is characterized by wavelengths between 10 m and 1 m, and UHF corresponds to the range from 1 m to 10 cm. The radars measure the winds by detecting backscatter from turbulent variations in the refractive index, i.e., humidity, temperature, and density variations. The measurement technique and many of the observations have been described by Gage and Balsley (1978), Balsley and Gage (1980), Röttger (1980), and Harper and Gordon (1980). Many of these coherent radars have high power transmitters and large antennas that enable them to detect the small backscattered power to altitudes in the stratosphere and mesosphere. The great sensitivity of the radars makes it feasible to obtain wind profiles with height and time resolution of the order of 100s of meters and minutes, making the technique a natural candidate for investigations of relatively small-scale phenomena. Indeed, a great deal of light is already being shed on the dynamics of the microscale in the troposphere and lower stratosphere, something about which little is known. It is only within the past few years that the usefulness of the radar data for applications in synoptic meteorology has become apparent. Because the topic has not been discussed fully in the past, we shall concentrate on this aspect.

The excellent time and height resolution afforded by the radars make them an excellent tool for investigating microscale dynamics. However, these same features are no less valuable for studies of larger scales. The high time resolution means that a better estimate of the wind over longer time scales is possible when the influence of the variability over short time scales can be eliminated by averaging. Rawinsonde data are not necessarily representative of the mean wind over the 12 h period between successive balloon launches. The radars also have the unique capability of measuring vertical velocities with great accuracy and good time resolution on a routine basis. Although vertical velocity measurements can be made by other techniques, the radars cannot be rivaled, as far as observing for long periods is concerned. Since so much of synoptic meteorology involves the prediction of vertical velocities, this facet makes the radar a valuable asset to the field in and of itself. It also has been discovered that meter-wavelength radars are capable of detecting inversions in the temperature profile. Enhanced reflections occur at a level just above the beginning of an inversion; this is providing valuable information about the height of the tropopause, as well as an interesting view of the structure of frontal systems.

The exchange of air between the stratosphere and troposphere at mid-latitudes occurs primarily in association with the tropopause folding mechanism that occurs at the junction between the cold-frontal surface and the troposphere. The intrusions of stratospheric air occur in regions with a horizontal scale of a few hundred kilometers and a vertical scale of 1 km (Holton, 1981). The radar measurements have the height resolution necessary to study this process in detail and provide the vertical velocity measurements that are needed to understand the dynamics of mixing across the tropopause.

All the topics mentioned above are far from being completely explored. Most of the areas of investigation are still in their infancy. However, the results to date already indicate the potential of the UHF and VHF Doppler radars for synoptic research and for studies of the interaction between the synoptic and mesoscale. In this review we shall present what we believe are some of the more interesting results of recent investigations in the field and discuss some of the possibilities for future research. We shall also touch on the feasibility of operational use of the radars.

2. The measurement technique

The general features of Doppler radar velocity measurements have been described by others (e.g., Wilson and Miller, 1972; Battan, 1973; Doviak *et al.*, 1979). We shall not review the basic theory (See Balsley and Gage (1982) in this issue for a complete review) but merely describe the particular aspects of the problem that relate to the UHF and VHF radars. The pulsed Doppler radars emit either a single pulse or a train of pulses of electromagnetic radiation, and some of the energy is backscattered when variations in the refractive index structure of the atmosphere at scales of half the radar wavelength are encountered. By measuring the frequency of the returned signal, the small change in frequency due to the motion of the scatterers can be determined. The Doppler shift in frequency can then be related directly to the line-of-sight velocity of the turbulent variations in the refractive index. If the turbulent variations are "frozen" in the medium during the time it takes to cross the radar beam (the Taylor hypothesis), the Doppler velocity is then a measure of the mean motion of the atmosphere over the volume that the radar illuminates.

The accuracy of the radar-deduced winds has been tested by comparisons of radar wind profiles and rawinsonde profiles from nearby stations (Balsley and Farley, 1976; Farley *et al.*, 1979; Strauch, 1981). However, a comparison between the measurements of a 6 m and a 3 cm radar also has been carried out (Strauch *et al.*, 1982). The microwave radar makes wind measurements indirectly by measuring the velocity of precipitating particles, but it is highly accurate, particularly when snow is present. The comparisons were carried out under the appropriate conditions and good agreement was achieved, thus circumventing the problem that usually arises when the radar measurements are compared to rawinsonde measurements. The agreement is usually good, but not perfect, and the differences are then attributed to variations over the spatial separation between the balloon ascent and the radar facility.

Given that the line-of-sight velocities can be obtained, there are three methods in use for determining the vector winds. The first is the VAD (velocity azimuth display) technique in which a steerable antenna beam, pointed at some angle off zenith, is used to measure the line-of-sight velocity as a function of azimuth and height (Lhermitte and Atlas, 1963; Wilson and Miller, 1972). If the winds do not vary over the cone traced out by the beam, and the velocity is strictly horizontal, the velocity measured by the radar will vary sinusoidally as a function of the azimuth. A nonzero vertical velocity component will create an offset in the sinusoid. The main advantage of the VAD technique is that in theory at least, variations of the winds over the sampling cone due to divergences or rotations in the wind field also can be resolved by this technique if more Fourier components than just the first order sinusoid are included in the fit. In spite of this advantage, the information has not really been put to practical use in any of the experiments that we are aware of. The other two techniques described next require the assumption of homogeneity in the wind over the spatial separation of the beams in order to resolve the vector wind. The major disadvantage of the VAD technique is that the need for a steerable dish antenna puts a practical limit on the antenna size.

The second method of determining the vector wind is to use a fixed dipole array (Woodman and Guillen, 1974). By phasing the signal fed to the various parts of the array, the transmitted beam can be moved off vertical. The vector wind can be determined uniquely by pointing beams in three different directions in what amounts to a simplified VAD technique. Usually one beam is pointed in the vertical direction and two in the off-vertical direction at an angle of 5° to 15°. The Poker Flat MST (Mesosphere, Stratosphere, Troposphere) radar is operated in this configuration, for example (Balsley *et al.*, 1980). The main advantages of this type of system are that the antenna is easy to construct and relatively inexpensive. Also, antenna arrays with dimensions as large as 200 m × 200 m can be utilized, something that would be very difficult with a steerable dish system. The disadvantages are that for large antennas, considerable real estate is involved

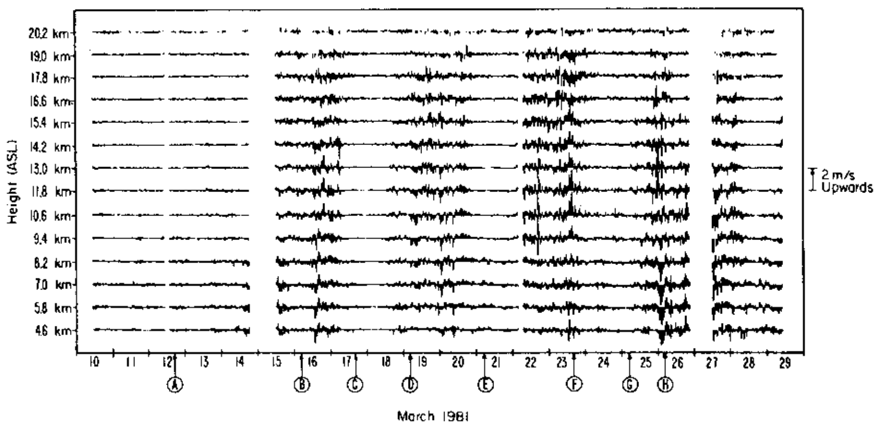

FIG. 1. Vertical velocities measured with the Platteville, Colo., 50 MHz radar. The reference scale is shown at the right-hand axis. The time series covers a period of 19 days, and the height resolution is 1.2 km. Alternating quiet and active periods repeat every four to five days.

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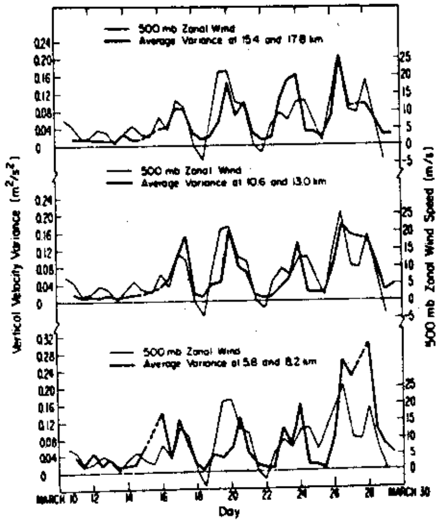

FIG. 2. Average variance in the vertical velocity at 15.4 and 17.8 km for the data shown in Fig. 1 compared to the 500 mb zonal wind measured by the Denver radiosonde. The variance was calculated for a 2 h period centered on the time of the radiosonde ascent.

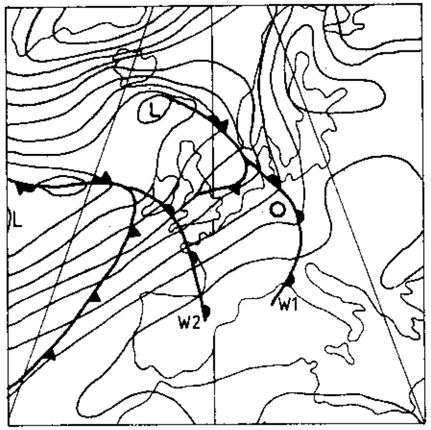

FIG. 3. Synoptic situation at 0000 GMT on 7 March 1981. The heavy circle shows the location of the SOUSY-VHF-radar. The radar data taken during the passage of the warm front labeled W2 are shown in Fig. 4.

and there is no way to take into account variations in the wind field over the distance separating the beams. The latter has not been a problem except during strong gravity wave events.

The third technique is the spaced antenna (SA) measurement advocated by Röttger and Vincent (1978) and Vincent and Röttger (1980). The capabilities of the SA method were compared to the two methods described above by Briggs (1980) and Röttger (1981a). For this method one transmitter array and three spatially separated receiver arrays are used. The horizontal wind components are determined by a correlation analysis of the signals measured at the three receiver arrays. The vertical velocity is found from the Doppler-shift of the radar echoes. As mentioned in the introduction, radars are particularly sensitive to temperature inversions and other stratified structures such as fronts. It has been determined that there is an enhanced reflectivity for radars operating at wavelengths of the order of meters when the radar beam is pointed vertically and that the returned power drops off very rapidly within a few degrees of vertical. Since the SA technique uses only vertically pointing beams, it is possible to detect echoes with a higher signal-to-noise ratio than those that could be detected with a system using an off-vertical beam configuration. The disadvantages of the SA method are essentially the same as those of the fixed dipole array method. Perhaps the SA radar handles inhomogeneities in the sampling volume slightly better than the Doppler method since the measurement, by its very nature, tends to average variations in the atmospheric structure between the two receiving antennas. Also, the vertical velocities can be measured in all three receiving beams simultaneously and this provides direct information on the spatial variations within the sampling volume.

The layered structures that enhance the reflectivity at vertical incidence may not be moving with the wind speed but may be modulated by waves or the slope of frontal surfaces, as we shall discuss later. In such cases, the measured vertical velocity will have a contribution both from the effect of the sloped surface as it moves through the beam and the real vertical wind. With three beams and good height resolution, the orientation of the layers can be determined. The vertical velocity measurements can then be corrected for this effect (See Appendix in Röttger, 1981c).

3. Modulation of vertical velocity fluctuations by planetary waves

Ecklund *et al.* (1981a,b) have used the Poker Flat, Alaska,

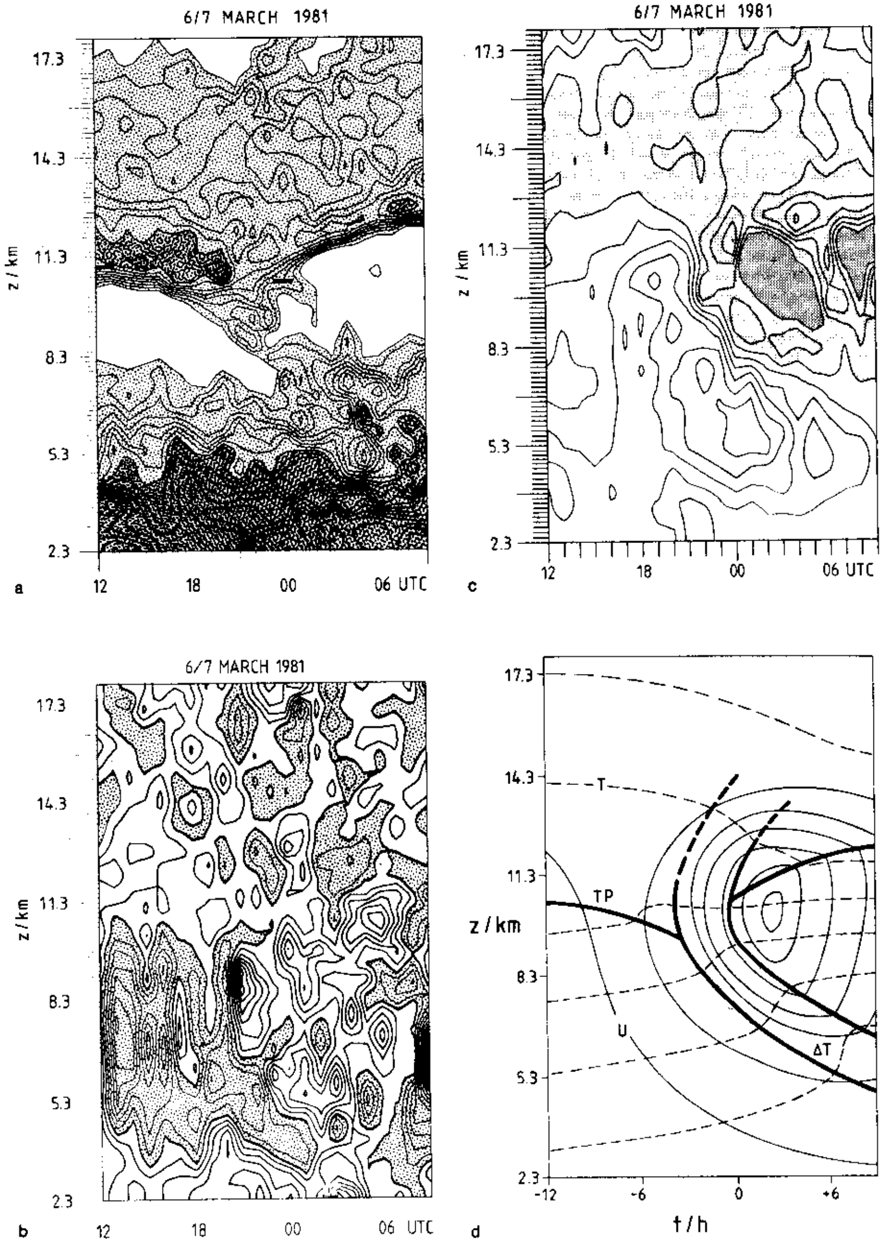

FIG. 4. a) Reflectivity contour plot. Difference between contour lines is 2 dB. Intensity of shading corresponds to intensity of echoes. b) Contour plot of vertical velocities. Shading indicates downward velocity. The interval between contours is 7.5 cm/s. c) Contour plot of wind speed with a contour interval of 2.5 m/s. Shading indicates speeds greater than 20 m/s. The heavy stippled areas correspond to missing wind data due to undersampling. d) Thermal structure and winds near fronts adapted from Palmén and Newton (1969). The heavy line labeled TP corresponds to the height of the tropopause. The dashed lines are the isotherms, and the solid lines are the isotachs. The jet is located on the warm side of the front just below the tropopause.

MST radar and the Platteville, Colo. radar, both of which operate at a frequency of 50 MHz, to study the nature of vertical velocity fluctuations over periods of several weeks. The 15 min. average vertical velocities for a three-week period in March at Platteville are shown in Fig. 1. It is evident that there are several days of low activity followed by 3 or 4 days of high activity. This pattern repeats during the observations. The period of the envelope modulating the vertical velocity variability is similar to the period of planetary-scale waves. Ecklund *et al.* (1981b) found that the 500 mb synoptic maps for the period indicated that the levels of high activity corresponded to periods when a strong zonal flow was present. This is shown more clearly in Fig. 2, which shows the vertical velocity variance at three different heights plotted together with the 500 mb zonal wind speed. There is clearly a good correlation between the two. The explanation by Ecklund *et al.* (1981b) was simply that it was an orographic effect associated with the mountains west of Platteville. The stronger the zonal flow, the larger the amplitude of the vertical velocity fluctuations associated with the gravity waves generated in the lee of the mountains.

Observations have been made simultaneously with the Platteville radar and the Sunset 50 MHz radar located in the mountains west of Boulder (Balsley *et al.*, 1981). Corresponding active and quiet periods were seen at both locations, but it was found that the magnitude of the variance at Sunset, located in the mountains, was much greater than that at Platteville, located on the plains east of the mountains.

It has long been known that the Continental Divide exerts a drag on the planetary-scale flow. General circulation models usually include some parameterization scheme to simulate this effect in order to make the simulations more realistic. The variance in the vertical velocities observed at Platteville and Sunset are indicators of the amount of damping of the zonal flow that is taking place. The energy taken out of the flow manifests itself as small-scale eddies or gravity waves. The fluctuations observed at Platteville should be particularly useful for estimating the damping, since the location is in the lee of the mountains.

The study by Ecklund *et al.* (1981a) showed a similar variability in the vertical velocity fluctuations at Poker Flat, with quiet and active periods alternating every 3 to 4 days. However, the implications of that study were slightly different. The terrain surrounding the Alaska site is not as well defined as that at Platteville. Indeed, no clear relationship that would indicate an orographic effect could be found between the direction or magnitude of the wind and the degree of activity. The strongest correlation was found when the average wind shear between 3.9 and 19.7 km altitude was plotted against the vertical velocity variance. The agreement between the two curves is not as good as that in Fig. 2, but there is enough similarity to raise the possibility that a dynamic interaction between the large-scale planetary waves and the short-period gravity wave oscillations accounted for the modulation pattern. A similar result was reported by Röttger (1981a). This effect will have to be examined in more detail to determine if such a relationship exists.

If it can be determined that planetary waves do modulate short period fluctuations in the vertical velocities, the radar measurements of vertical velocities could be important in improving our understanding of how the synoptic and mesoscales interact. This would appear to offer a great potential for application of the radar technique. Klostermeyer (1981) has discussed the application of the technique to other studies of the interaction of different scales.

The time series in Fig. 1 show that some averaging will certainly be necessary if the mean vertical velocity measured by the radars is to be representative of the synoptic situation. It is still to be determined if effects due to wave perturbations can be averaged out in such a way that the result is meaningful. G. Nastrom (personal communication, 1982) is presently investigating these questions by comparing the long time series of vertical velocities measured by the Poker Flat MST radar with the vertical velocities derived from radiosonde data using the quasi-geostrophic ω equation and other techniques.

4. Observations of frontal passages

Röttger (1979) and Röttger and Schmidt (1981) have made observations of warm frontal passages with the SOUSY/VHF radar located in the Harz mountains in Germany. Figure 3 shows the synoptic situation at 0000 GMT on 7 March 1981. The location of the SOUSY radar is indicated by a heavy circle. The map shows that the area was affected by two lows, one centered near Iceland and the other centered due west of England. Each low is characterized by a distinct set of fronts. The warm front labeled W1 shows signs of occlusion, as does the one labeled W2. Radar data are available for the passage of the second warm front at the SOUSY site. Figures 4a–d show contours of the radar reflectivity, the vertical velocity, the magnitude of the horizontal velocity, and a schematic representation of the structure of a front taken from Palmén and Newton (1969).

The fact that the VHF radar sees the frontal structure so clearly is due to its sensitivity to thermal stratification in the atmosphere (Green and Gage, 1980; Rastogi and Röttger, 1982) as we have already discussed. The schematic in Fig. 4d can be compared to the reflectivity contours in Fig. 4a. Not only is the comparison quite good in terms of the ability of the radar in locating the position of the front, but the schematic helps to show the temperature gradients that are associated with the increases in reflected power. Figure 4b shows the area of ascent in the warm sector of the front and the area of subsidence in the cold sector. At the time between 1800 and 2300 UT a fingered structure in the vertical velocity field is present immediately ahead of and in the area of the juncture of the warm frontal surface and the tropopause bound-

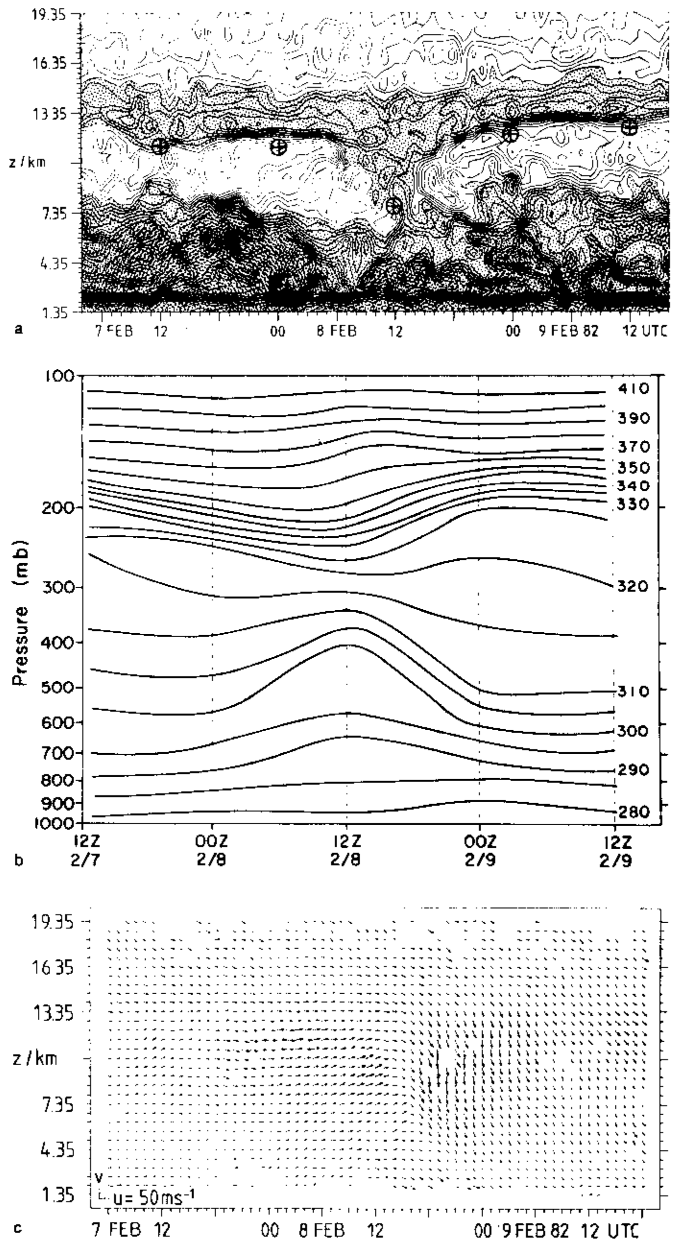

FIG. 5. a) Reflectivity contours for a warm-frontal passage observed with the SOUSY-VHF-radar during February 1982. Shading and contour levels are the same as in Fig. 4a. The crosshairs show the position of the tropopause reported by the radiosonde station at Hanover, 50 km from the site of the radar. b) Pressure-time cross-section of the potential temperature measured by the Hanover radiosonde during the period corresponding to the data in Fig. 5a. The contour interval is 5 K in the troposphere. Above 350 K isotherm, the contour interval was increased to 10 K. c) Wind vectors measured by the radar as a function of time and height. The reference scale and directions are shown at the lower left-hand corner.

ary. There is an intrusion of stratospheric air at 2000 UT. The fingered structure associated with this event is reminiscent of the tropopause folds responsible for mixing that have been observed and discussed by Shapiro (1974, 1978).

It has to be admitted, however, that the vertical velocities measured with the radar may be contaminated by a small contribution due to the horizontal wind, if the refractive index structures are inclined to the horizontal. This is a typical feature of frontal systems and also will occur during strong gravity wave activity, e.g., lee waves. This effect can be compensated for by measuring the inclination angle with the spaced antenna set-up and applying a correction to the vertical velocities (see Appendix in Röttger, 1981c).

All the data were measured during a period of only 12 min on the full hour during the frontal passage. Thus, the vertical velocities shown in Fig. 4 are the averages for the 12 min periods and may not be representative of the conditions throughout the hour. However, the overall velocity fields are downward in the cold air and upward in the warm air. This is consistent with the expected pattern. Also, although we cannot comment on the variability in the fingered structure, there is no doubt that it is present.

The horizontal velocity cross section in Fig. 4c is very similar to the schematic structure of the winds shown in Fig. 4d. The data in the heavy stippled area in Fig. 4c have been omitted because the signal was undersampled during this particular series of observations. The radiosonde data for this period indicate a wind maximum in this region, in agreement with the schematic of Fig. 4d.

Röttger and Schmidt (1981) used the horizontal wind vector data measured by the radar to calculate the horizontal temperature gradients from the thermal wind relation. In general, good agreement between the derived and observed values was found in the height region between 700 mb and 300 mb. However, Shapiro (1974) showed that the geostrophic relation, and the thermal wind relation that it implies, can be found to explain the balance near frontal zones in a fortuitous manner. It may be that the balance is only apparent since two large gradient wind terms cancel each other. The high time resolution measurements that are possible with the VHF radar, such as those shown in Figs. 4 and 5, make it possible to get a better estimate of the peak wind associated with a jet stream than is possible with radiosondes launched every 12 h. Also, the areas of jet-stream generated turbulence can be located. Further radar observations of jet streams and their mesoscale variability have been made by Gage and Clark (1978), and Rüster and Czechowsky (1980).

Figures 5a–c show data taken with the SOUSY radar during a warm frontal passage on 8 February 1982. Figure 5a represents the contours of reflectivity, with darker shading indicating stronger echoes. The pattern is very similar to that seen in Fig. 4a. The circles with crosses are the tropopause heights reported by the Hanover radiosonde station, 50 km from the site of the radar. A large gradient in radar reflectivity is evident at the height where the tropopause occurs. At 1200 UT on 8 February, the tropopause is almost 4 km lower than reported at 0000 UT due to the passage of the warm front, and there is good agreement between the radar and radiosonde observations. The time-pressure cross-section of potential temperature at Hanover for the same period is shown in Fig. 5b for comparison with the radar reflectivities. The position of the frontal boundary is defined by the 300–310 K isotherms between 1200 UT (Z) on 8 February and 0000 UT on 9 February. Figure 5c shows the horizontal wind vectors measured by the radar as a function of height and time. The wind shift from roughly westerly on the cold side to northerly winds on the warm side of the front can be seen. The jet core passes the radar at 1700 UT on 8 February and is located at 10 km ASL. These observations are described in more detail by Larsen and Röttger (1982). The comparison between the radar and radiosonde data for this particular case not only points out the agreement between the two but also shows the details in the frontal structure that are missed by the 12 h radiosonde ascents.

The results of the observation of the frontal passage are only preliminary. The mixing between the stratosphere and troposphere will be investigated by analyzing cross sections of potential vorticity and potential temperature as suggested by Danielsen (1968) and comparing that to the vertical velocity data available. Radiosonde data also will be used to check the thermal wind relation more carefully. Finally, the position of the front can be determined based on radiosonde data and this can be compared to the position determined from the radar reflectivity. The good time resolution and height resolution of the radars may help to improve our understanding of the mixing of air that is part of the damping process for the frontal system, as well as providing a new tool for forecasting on shorter time scales (Röttger, 1981b). The vertical velocity measurements also should improve our understanding of how precipitation develops in association with the frontal structure. The combination of the radiosonde data and the Doppler radar data is particularly powerful for studying the interaction of the synoptic scale and the mesoscale.

5. Turbulence in the atmospheric mesoscale

Most of the large radar facilities capable of measuring winds throughout the troposphere and in the lower stratosphere were originally designed with other purposes in mind. Though meteorological research is being carried out at most of these facilities, only the SOUSY-VHF-radar, the Platteville radar, the Sunset radar (Green and Gage, 1980), and the Poker Flat MST radar (Balsley *et al.*, 1980) are being operated in a mode dedicated to observation of the atmosphere. Of these, the Poker Flat radar is unique in that it has been in operation continuously since the latter part of 1978, obtaining one complete profile every 4 min with a 2.2 km height resolution. This unique data set is ideal for investigations of atmospheric dynamics at both long and short time scales. At the present time the Platteville radar also is operating in a continuous mode as part of an effort by the Wave Propagation Laboratory of NOAA to establish a mesoscale prediction network (Strauch *et al.*, 1982), but the data it is providing are not as detailed. The system will eventually include three VHF radars located in a triangle around Denver, Colo., and will provide wind profiles in the troposphere in an operational mode similar to that of the Poker Flat facility. The WPL system will be described in more detail in a later section.

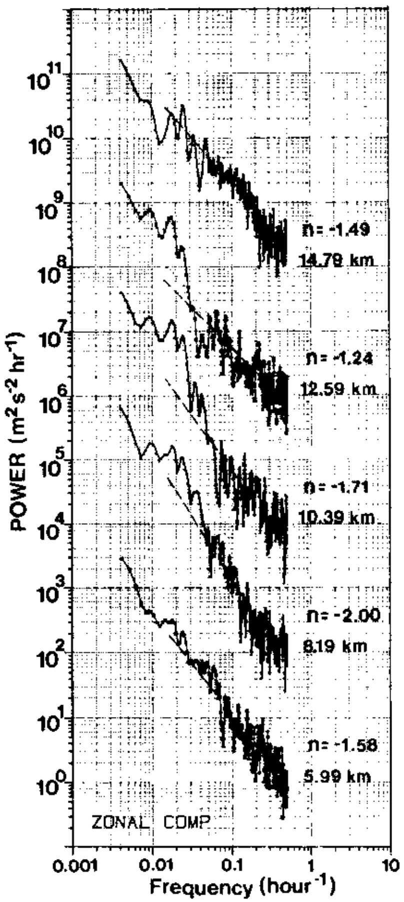

FIG. 6. Power spectra calculated from a 40-day series of wind measurements made with the Poker Flat, Alaska, MST radar. Each successive curve has been multiplied by a factor of 100. The left-hand scale is correct for the spectrum at a 5.99 km altitude. A curve of the form $P = P_0(f/f_0)^n$ was fit to the spectrum at each height, and the value of n is indicated next to each curve. The average value of the slope is $n = 1.602 \pm 0.250$.

Larsen *et al.* (1982) used the Poker Flat horizontal winds for a 40-day period from 25 February to 5 April 1979 to investigate turbulence in the mesoscale. Wind data were available on a nearly continuous basis at heights ranging from 5.99 km to 14.69 km at 2.2 km intervals. The resulting spectra for the zonal wind component are shown in Fig. 6. Corresponding to each height is the spectral index n which was determined

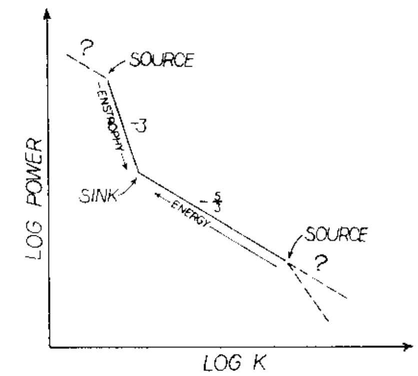

FIG. 7. Schematic representation of the energy and enstrophy flow if the $-5/3$ slope derived from the data in Fig. 6 is representative of 2-dimensional rather than 3-dimensional turbulence. The source at high wave numbers could be due to convection or small-scale wave energy generated by shear instabilities.

by least-squares fitting a power law of the form

$$P(f) = P_0(f/f_0)^n$$

to each of the spectra. Here f_0 is a reference frequency corresponding to the point in the spectrum where the power is P_0. The average value of n was found to be 1.602 ± 0.25, very close to a value of $-5/3$. The spectra for the meridional wind component are not shown but were very similar and had the same spectral index.

Gage (1979) reviewed the results from diverse studies of turbulence at scales from a few hours to a few days and pointed out that a common thread was the finding of a $-5/3$ power law. Most, though not all, of these studies used data in the frequency domain. However, if the Taylor hypothesis is valid so that eddies can be considered to be moving with the mean wind over the sampling period, then a $k^{-5/3}$ power law is implied. Gage further postulated that at these large scales the turbulence is 2-dimensional rather than 3-dimensional. Following Kraichnan's (1967) theory, this would imply that a source of energy exists at small scales and energy is transferred up the spectrum toward larger scales in what has been termed a "red cascade."

Lilly (1982) has expanded the theory of 2-dimensional turbulence at these scales and has shown that 3-dimensional internal wave structure can coexist with 2-dimensional turbulent eddies relatively independent of the other. Lilly pointed out that an energy source due to convection or small-scale shear instabilities would occur in a 3-dimensional range but could leak enough energy into the 2-dimensional range to account for the observations. The energy and enstrophy flow are shown schematically in Fig. 7. At scales larger than 1000 km a k^{-3} enstrophy cascade range of 2-dimensional turbulence exists (see, e.g., Julian *et al.*, 1970).

Van Zandt (1982) has proposed that the observations also can be explained if the spectra are due to a universal Garrett-

Munk type spectrum, which is well known in the oceans. The implication would be that a gravity wave spectrum exists with interaction between different wavenumbers. The direction of the energy cascade would be the same as that of the 2-dimensional turbulence, but the dynamics would be inherently 3-dimensional. The question of which view is correct still needs to be resolved.

The spectra in Fig. 6 show a pronounced peak at a period of 50 h, very close to the 51 h period of the wavenumber 3 mode, two-day Rossby wave (see Salby, 1981). Salby's (1981) calculations indicate that the wave should be observable, though with a small amplitude, at latitudes corresponding to that of Poker Flat and for the time of year of the observations. Yet, it is clearly a significant feature of the wind variations during the observation period.

6. An examination of objective analysis schemes

The method used for interpolating observed data, usually from radiosondes, to a regularly spaced grid suitable for input to a numerical model, is termed objective analysis. The various schemes used for this process are designed to operate under two constraints. First, the value calculated for a given grid point should be representative of the true value of the parameter such as height of an isobar, temperature, or wind, at that grid point, corresponding to a scale size no smaller than the smallest scale that can be resolved by the model. Second, the derived values have to provide a balanced field to minimize the generation of spurious oscillations that can create errors in a numerical integration (see, e.g., Kruger, 1969). The first constraint is usually handled by providing a good initial guess of the value at the grid point and weighting it with observed values within a predetermined radius of influence of the grid point. This approach provides reasonable values in data-sparse areas and smooths out errors due to observational inaccuracies or oscillations, with characteristic scales smaller than the numerical model can handle. The second constraint can be met by requiring that the derived wind and height fields are in geostrophic balance. This is the simplest approach. A more complex approach is to require that the balance equation should be satisfied or that all the derived fields can be described by the normal modes of the numerical model (Daley, 1981).

A check on a scheme that requires geostrophy for balance would be to compare the geostrophic wind calculated from the derived height field to the actual geostrophic wind if a good estimate of that quantity is available, but it has been difficult to do in practice. Therefore, more elaborate schemes have been devised to test the various objective analysis schemes. Often the test has been a comparison of the output after application of the analysis procedure to a subjective analysis of the same data (Kruger, 1969; Otto-Bliesner *et al.*, 1977).

Larsen *et al.* (1981) used the data base from the Poker Flat radar described in the previous section to evaluate the Cressman (1959) and Gandin (1963) objective analysis methods. These schemes use a parabolic and a Gaussian weighting function, respectively, and are univariate. The weighting is

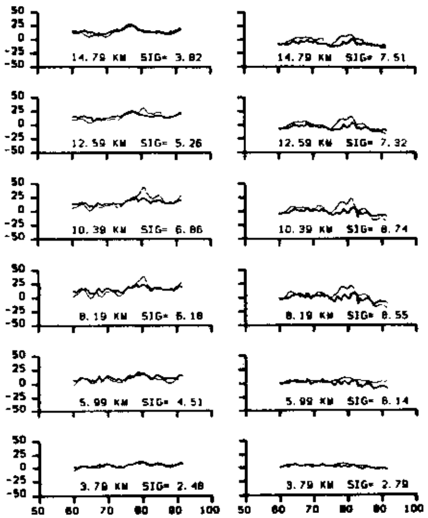

FIG. 8. Comparison of the radar winds averaged over 48 h centered on the time of radiosonde ascents (light line) and the geostrophic wind calculated from a grid of height data for isobaric surfaces (heavy line). The geopotential-height grid was calculated by applying the Cressman objective analysis scheme to the available radiosonde data from five stations located near the Poker Flat MST radar. The left-hand scale is velocity in m/s. The six curves on the right are for the meridional wind component. The quantity "sigma" is the rms difference between the two curves. The horizontal scale is Julian days.

only a function of radial distance from the grid point. The geostrophic wind calculated from the gridded values of the height field was compared to averages of the radar wind data over various time intervals centered on 0000 GMT and 1200 GMT, the times of the standard NWS radiosonde ascents. The rationale was that averaging of the 4 min wind measurements over periods of several hours should produce a good estimate of the balanced wind component, though the appropriate averaging interval had to be determined by trial and error. Since the radar provides many profiles in a 12 h period, as opposed to only one by the radiosonde, these can be averaged to produce a better estimate of the wind without the influence of meteorological noise.

The objective analysis schemes tested are the simplest ones that are available. However, the results have implications for the more complex multivariate optimum-interpolation schemes, since additional data for the interpolation scheme are gained by relating the height and wind fields through the geostrophic relation (Williamson *et al.*, 1981; Schlatter, 1975; Rutherford, 1972). The gradient wind relation is generally not used since it makes the problem nonlinear and thus more difficult to solve.

An example of the result of the comparison is shown in Fig. 8. The thin line represents a 48 h average of the radar

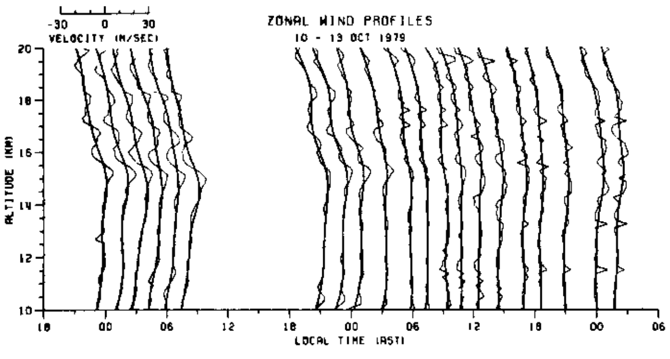

FIG. 9. Mean zonal wind profile and perturbations during a 48 h period measured with the Arecibo Observatory 430 MHz radar. Waves with a vertical wavelength of 1–2 km are present and a downward phase progression can be seen, at least in the first 6 h. A more detailed analysis has revealed that the wave period is close to 4 days.

winds measured every 4 min. The heavy line is the geostrophic wind determined by the application of the Cressman method with a radius of influence of 750 km to height data from five radiosonde stations surrounding the Poker Flat site. The results of the study show that there is essentially no difference between the Cressman and Gandin methods. For both of these schemes the optimum radius of influence is smaller than that conventionally used. For the Cressman method a commonly used radius is a little over 2000 km. The comparison indicated an optimum value of 750 km. Also, the Cressman analysis is usually applied in a series of successive scans in which the radius of influence is successively decreased to improve the estimate of variations at smaller scales. The comparison with the radar data indicated that this produces a result slightly poorer than a single scan with the optimum radius of 750 km. Finally, the difference between the geostrophic wind component and the radar wind component decreased rapidly as the averaging interval was increased out to 48 h. Beyond 48 h of averaging the difference decreased, but only slightly.

There is great potential for more studies of this kind that rely on the ability of the radar to provide good estimates of the winds free of the errors due to short term variability of the atmosphere. This type of study is not only important with regard to research but also will be important in assessing possible benefits of operational use of the radars. An investigation of a multivariate scheme using the radar and radiosonde data is planned for the near future.

7. Detection of tropical waves and tides

Wind measurements made at the Arecibo Observatory by Sato and Woodman (1982) using the 430 MHz radar always show perturbations in the vertical profile with a scale size of ~1 km. The perturbations usually only undergo one complete oscillation in the vertical direction, so it is difficult to speak of a wave train. There is very little vertical phase progression over a period of a few hours. Observations over a period of 48 h have shown that there is indeed vertical phase progression, but on a scale of several days. This is shown in Fig. 9, which presents a series of wind profiles from that experiment. It was determined that the period of the wave was likely to be four or five days. However, the observational period was too short to determine it accurately. Fukao *et al.* (1981) have seen the same kind of wave at Jicamarca, Peru, during a 48 h observation period. They also estimated the period of the wave to be between four and five days.

The period and the wavelength are characteristic of a mixed Rossby-gravity wave, which is an important part of the dynamics at low latitudes (see, e.g., Holton, 1975). Since the period is of the order of days, the high time resolution of the radars is not really necessary to observe the wave, but the high spatial resolution is, since the vertical wavelength is so small. Cadet and Teitelbaum (1979) detected the mixed Rossby-gravity wave in data taken during the GATE experiment. It was possible to resolve the wave structure because radars with high spatial resolution had been used to track the rawinsondes launched during the experiment. With the radars it will be possible to observe the waves on a more routine basis.

The ability of the VHF radars to measure vertical velocities on a routine basis also can have important consequences for tropical meteorology. Little work has been done in this regard to date, but it should be possible to improve our understanding of the interaction of the waves in the easterlies and the convection that they trigger on the cloud cluster scales. Radars operating at meter wavelengths can measure both the vertical velocities within the clouds and the centimeter per second vertical velocities associated with the waves. Over longer observation intervals, the annual transport of mass across the tropopause boundary associated with the tropical branch of the Hadley cell also could be studied.

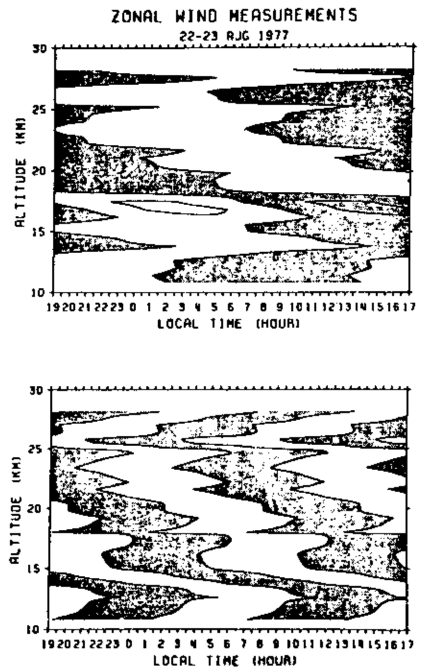

FIG. 10. Diurnal and semi-diurnal tidal components measured by Fukao *et al.* (1980) at Arecibo, Puerto Rico. The velocity time series were filtered to exclude everything but the particular frequency component of interest. The tidal components show downward phase progression and upward energy propagation in the lower stratosphere.

Fukao *et al.* (1980) have used the Arecibo radar to study the dynamics of the diurnal and semidiurnal tidal components. Figure 10 shows a time series over a period of 24 h which has been filtered to exclude frequency components other than those of the tides. The phase progression indicates that the source of energy for the diurnal tide is in the troposphere and is in agreement with the results of Wallace and Tadd (1974), whose investigation based on radiosonde data showed that the strong diurnal component seen in the troposphere at low latitudes is not the classical tidal component. Rather, it is driven by the interaction of the flow with the orography or some other input of energy in the troposphere. Fukao *et al.* (1978) have observed the semidiurnal and diurnal tides at Jicamarca, Peru, but they found that the semidiurnal tide dominated in the troposphere and the diurnal tide could only be seen in the stratosphere. This may be an indication that the energy source for the tropospheric diurnal tide seen at Arecibo is very localized.

8. The Wave Propagation Laboratory profiler

The first real attempt at operational use of the UHF/VHF Doppler radar wind measurements is as part of a system developed by the Wave Propagation Laboratory (WPL) of NOAA. The system is designed to be competitive with the NWS radiosonde (Hogg *et al.*, 1980; Strauch, 1981; Strauch *et al.*, 1982). The prototype Profiler consists of a dual wavelength radiometer that measures total precipitable water vapor content and vapor profiles, a microwave radiometer that provides temperature profiles, a UHF radar for wind profiling, and a VHF radar that determines the height of the tropopause and provides wind information. The standard surface measurements also are taken by the system. The drawbacks of the system are that the microwave technique does not provide a detailed profile of the water vapor content of the atmosphere as a function of height. However, the total precipitable water vapor measurements have been found to be in good agreement with the same quantity measured by radiosonde (Hogg *et al.*, 1980). The temperature profile determined by using the microwave radiometer is far less detailed than that of the radiosonde, but it may be that the resolution of the radiometer measurement will be sufficient for synoptic forecasting.

The system has been designed to provide data roughly every half hour. Most of the components of the system are located at the airport in Denver, Colo., and the VHF radar is located at Platteville, Colo. At the present time it mainly provides data on the height of the tropopause and other inversions. This information was found to be valuable in increasing the accuracy of the radiometer temperature profiles (Strauch, 1981). Eventually three more VHF radars for wind profiling are planned as part of the PROFS (Prototype Regional Observing and Forecasting Service) program. These radars will be located in a triangle around Denver, about 150 to 200 km from the airport site. It is expected that data from the total system will be used to increase flight safety, decrease airplane fuel consumption, and significantly improve short-term forecasting.

As the present review indicates, the UHF and VHF radars have mostly been used as tools for research in the past, although the potential for operational use has been realized for a number of years. The WPL effort is the first dedicated evaluation of the synoptic potential of the radar wind measurement system. The radar by itself could never replace the radiosonde, since there are no means of determining the thermodynamic variables from the radar measurements. The addition of the radiometer temperature measurements to the radar-derived wind profiles makes the system a much more serious competitor for the radiosonde. However, the water vapor measurements are still not detailed enough to provide adequate information even for synoptic-scale forecasting.

Regardless of whether the radar systems replace the radiosonde network, they have certain characteristics that would at least argue for an eventual fusion of the two types of networks. The radars provide very reliable measurements and little routine maintenance is needed. The wind data can be processed completely automatically, and the measurements can be made regardless of the state of the weather (Gage and Balsley, 1978; Hogg *et al.*, 1980). Thus, the system is ideal for operation in remote places where few data are available otherwise. In fact, Balsley and Gage (1980) have proposed that a series of buoys equipped with Yagi antennas could provide wind measurements up to the tropopause level. The data would be processed onboard and sent via satellite to the data collection center. Possible problems with this idea are that there might be contamination of the wind data due to sea clutter detected in the side lobes, and the antenna area will necessarily have to be rather small. However, if these problems can be solved, such a system would give a tremendous improvement in the data coverage over the oceans, where so few data are available now.

9. Conclusion

We have presented a sample of recent results obtained by applying the UHF/VHF Doppler radar technique to synoptic research. The review is by no means exhaustive but should provide a general idea of the direction of research in the field so far. There is little doubt that the radars will become an important research tool for studies of synoptic scale dynamics. The improved temporal resolution along with the capability of vertical velocity measurements is opening new avenues of inquiry. The characteristics of the radars seem to be particularly suited to investigations of the interaction between the synoptic scale and the mesoscale, as the results covered in this review indicate.

There appears to be a great potential for operational use of the radar measurements. What direction the development of the systems will take is still not quite certain, but the efforts of the Wave Propagation Laboratory of NOAA in testing their Profiler system will help to determine the course. Further testing of the radar/radiometer measurement technique for synoptic purposes is needed, not only to determine if the functions of the radiosonde network can be replaced or augmented by this technique, but also to evaluate the possibility of using the radar system as a data gathering technique for remote areas.

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