Case Studies of the Vertical Velocity Seen by the Flatland Radar Compared with Indirectly Computed Values

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ABSTRACT

The hypothesis that temporal averages of vertical motions over a single radar station are representative of weather systems large enough to be resolved by the radiosonde network is tested using data from the Flatland VHF radar, located in the very flat terrain of central Illinois. Six-hourly means of radar data were compared with four separate estimates of the synoptic or subsynoptic-scale vertical motions computed using the dynamical equations with unsmoothed rawinsonde data and with NMC gridded analyses. Spring and fall cases of large upward and downward vertical motions were selected for study. During the course of this study it was found that contamination of the Doppler radar spectra by heavy or moderate precipitation must be taken into account during analyses of VHF radar data in the troposphere.

The signs of the vertical-motion estimates from the indirect schemes in the extreme cases selected for study here nearly always agree, although the magnitudes often differ by a factor up to about 4. The adiabatic method was found to be unrepresentative due to the large time separation of radiosonde measurements. The 6-h average radar observations usually fall within the envelope of estimates from the various indirect methods. The major source of statistical uncertainty of the temporal means of the vertical motions seen by the radar is the mesoscale structure seen in shorter-period averages and not completely filtered out during averaging. Such structure is not resolved by the radiosonde network data and analyses.

1. Introduction

Time series of vertical velocity measurements from MST (mesosphere–stratosphere–troposphere) radars (wind profilers) typically show a rich spectrum of variability. The largest fluctuations are seen at time scales of a few tens of minutes. Statistically, the short-period fluctuations are consistent with a spectrum of gravity waves subject to Doppler shifting by the mean wind (VanZandt et al. 1991). The spectrum of vertical motions usually shows peak amplitude near 15-min period and decreasing energy densities as periods lengthen from those that are associated with larger mesoscale motions to those that are associated with the synoptic and subsynoptic scale. Nevertheless, there is a growing body of evidence showing that means of the vertical motions taken over time periods on the order of an hour seen by MST radars are associated with vigorous mesoscale weather systems. For example, case studies during the passages of baroclinic storms show that the vertical velocities observed by MST radars are consistent with established models of the secondary circulations in mesoscale systems such as jet streams, fronts, and tropopause folding events (e.g., Larsen and Rotger 1982; Green et al. 1988; Nastrom et al. 1989; Crochet et al. 1990). However, there is less evidence that long-period temporal averages of vertical motions measured over a single station could be used to represent synoptic- or subsynoptic-scale weather systems.

It is of interest to ask whether time averages of MST radar observations represent the vertical motion of the synoptic- or subsynoptic-scale flow in quasigeostrophic
systems. Although it is generally agreed that much of the vertical mass flux in baroclinic systems is due to mesoscale circulation features (Wallace and Hobbs 1977, p. 436), these features are not well resolved by the radiosonde sounding network. Furthermore, many of our present meteorological analysis schemes are based solely on inferences of the large-scale vertical motions. Yet, although an abundant literature has developed over the last half-century dealing with methods to estimate the vertical motions associated with the large-scale flow from radiosonde data (e.g., as reviewed recently by Dunn 1991), there is still no consensus on the best method to estimate vertical motions (e.g., Barnes 1986; Durran and Snellman 1987, 1988; Fuelberg and Funk 1987; Portis and Lamb 1988; Lai 1988; Doswell 1989; Van den Dool 1990). Direct observations by wind profilers may address this problem.

However, temporal averages of vertical motions from MST radars can aid in diagnosis of atmospheric processes only if the conditions under which they represent the large-scale flow are understood. Attempts to study the vertical velocities of large-scale systems at MST radar sites near mountains have been frustrated by the presence of orographic effects that usually overwhelm any large-scale signal present (Nastrom et al. 1985; Larsen et al. 1988; Sato 1990). Thus, the 50-MHz Flatland radar was built in the extremely flat terrain of central Illinois to study motions far from orographic influences (Green et al. 1988).

The purpose of this paper is to present results from case studies of vertical motions at the Flatland radar testing the hypothesis that synoptic- or subsynoptic-scale vertical motions can be observed using a VHF radar. The results show that, provided effects of precipitation are taken into account, a distinct signal associated with large-scale weather systems is present in the radar vertical-motion data, although there is often relatively large statistical uncertainty in its magnitude. Most of this uncertainty is due to large-amplitude mesoscale features that cannot be adequately filtered out during temporal averaging.

2. Case studies

a. Method and data

A case study approach is used. Temporal means of the vertical velocities measured by the Flatland radar are compared with vertical motions computed using radiosonde data and National Meteorological Center (NMC) analyses.

Vertical motions were computed for all days in March–April and September–October 1990. The radiosonde data are available at 0000 and 1200 UTC daily. The sounding times with largest computed upward and largest downward motion at 500 hPa (about 5.6 km above sea level) in the spring and fall were selected for presentation here. The operational surface synoptic weather maps for these four cases, given in Fig. 1, will be discussed in detail as each case is presented.

Vertical motions were computed by four methods. First, the kinematic method was used with the triangle of standard rawinsonde sites around Flatland (Peoria, Illinois; Dayton, Ohio; Paducah, Kentucky; see Fig. 1). The common assumption that vertical motions are uniform across the triangle was made. Vertical motions were computed by integrating the continuity equation in pressure coordinates upward from 900 hPa in 50-hPa increments to 200 hPa. Ekman pumping due to frictional convergence was used as the lower boundary condition. Following O’Brien (1970), a correction was applied to each profile assuming the vertical motion is zero at the tropopause, taken to be 200 hPa. Finally, the vertical motions were converted to height coordinates as described by Nastrom et al. (1985).

The vertical motions over Flatland were also computed by a generalized form of the omega equation (Pauley and Nieman 1992) using gridded NMC analyses with homogeneous boundary conditions, as well as a gridpoint version of the kinematic method with an O’Brien correction. These vertical-motion estimates had extreme upward and downward values at 500 hPa in the same cases chosen using the triangle of balloon sites.

The NMC gridded analyses used to compute the generalized and kinematic vertical motions were obtained from the NMC regional optimum interpolation (ROI), which is the analysis method used to initialize the NMC Nested Grid Model (NGM). The ROI analysis operational in 1990 (DiMego 1988) was performed on a “thinned” 1.5° latitude × 2° longitude grid on the 16 NGM terrain-following sigma levels. The analysis was then interpolated to mandatory pressure levels on the 190.5-km polar-stereographic mesh used for NMC’s Limited-Area Fine-Mesh Model (LFM) and archived at NMC. The full-resolution analyses were only available in real time and so could not be used for this research. The archived analyses were interpolated linearly in the logarithm of pressure to standard pressure levels at an interval of 50 hPa. Fields of wind, height, temperature, and humidity from the five lowest model sigma levels were also used in this interpolation. The vertical motions were computed from this interpolated dataset. The use of this relatively coarse grid would be expected to yield vertical motions somewhat weaker than would be obtained from the full-resolution analysis. However, the horizontal resolution of the LFM grid is quite reasonable in light of the distribution of the North American rawinsonde network, which has an average separation of 400 km. On the NMC grid, computations were made with the omega equation and by the kinematic method at grid points and then interpolated horizontally to the Flatland location.

Finally, the adiabatic method as described by Nastrom et al. (1985) was applied using the rawinsonde data. In the adiabatic method it is assumed that any
imbalance in the local temperature tendency and horizontal temperature advection is offset by adiabatic warming or cooling due to vertical motions. This method often gave widely different estimates from the other methods and appears unreliable in the cases studied here. This failure is probably because, to calculate time derivatives, 24-h time differences are required by the available 12-h radiosonde data. The systems studied here were rapidly evolving with large changes over periods less than 24 h. Thus, we conclude that the adiabatic method is not reliable under such conditions, and results from the adiabatic method will not be displayed.

Radar observations of the vertical velocity were recorded at approximately 2-min intervals in range gates spaced at 750-m intervals from 2 to 16.25 km. Data from the lowest range gate are often unreliable due to T–R (transmit–receive) switch recovery problems. The declining signal-to-noise ratio with altitude often places the upper limit of useful data near 10 km. The Flatland radar has been built in stages. During 1990 the system was upgraded to a five-beam configuration with one beam directed vertically and four beams directed 15° off vertical in each cardinal direction. Other details on the radar and its operation are given by Green et al. (1988) and Warnock et al. (1993).

Vertical velocity \( w \) can be estimated using two oblique beams pointed in opposite directions assuming the mean motions are the same in both sample volumes (Vincent and Reid 1983). Thus, three estimates of \( w \) were available from the Flatland radar data: from the vertically directed beam and from the oblique pairs in the east–west and north–south planes. Simultaneous estimates of the hourly mean \( w \) are highly correlated; for example, during 2–8 October 1990 the average correlation of the vertical beam \( w \) with the north–south pair \( w \) was 0.83 (the east–west antenna had a receiver problem during this period). Over longer periods the mean values agree within the bounds of sampling uncertainty (Nastrom et al. 1993). Vertical velocities from the vertical beam will be used for the comparisons here since data in the vertical beam are usually more complete.

The typical spacing of radiosonde stations in the vicinity of Flatland is about 450 km. For a typical horizontal wind speed of 20 m s\(^{-1}\), air parcels travel this distance in about 6 h. In this paper, 6-h averages of the MST radar data are used.

b. Comparisons

The spring case with largest downward motions at 500 hPa from the kinematic method was for 0000 UTC

![Fig. 2. Comparisons of the vertical velocities over Flatland during spring cases (0000 UTC 23 March 1990; 1200 UTC 8 March 1990) computed from radiosonde or NMC data by several methods and 6-h means from the Flatland radar data.](image-url)
23 March 1990. The downward flow occurred during strong surface pressure rises under cold-air advection following the passage of an active surface cold front. The surface front (Fig. 1) that passed Flatland shortly after 1800 UTC 22 March produced a brief period of strong upward vertical velocities in the midtroposphere from 1800 to 2100 UTC, followed by widespread strong sinking motion after about 2100 UTC. These motion patterns are indicated by the radar observations, discussed more below, and by the surface weather reports (not shown).

All of the indirect methods give downward motions at 0000 UTC 23 March 1990 except the kinematic method based on NMC data (Fig. 2). Magnitudes of these estimates range up to about 12 cm s⁻¹. The 6-h mean w’s from the radar data have magnitudes well within the envelope of the indirect estimates. In this case they are the most similar to the generalized omega equation results.

The amount of variability due to mesoscale structure that is filtered out by using 6-h means of radar data is illustrated in Fig. 3 by the comparison of the ensemble of profiles of 1-h means with the 6-h mean (the solid line). Typically, the hourly values are based on about 22 observations and have standard deviations of 15–30 cm s⁻¹. The 1-h means show downward motions, as expected from analysis of the synoptic weather situation, with some notable exceptions of upward w from about 6 to 9 km at 0100 to 0300 UTC. Inspection of the surface chart at 0300 UTC and the upper-air charts at 0000 UTC revealed no feature that could be used to explain or anticipate this brief period of upward motion. We conclude the upward motion must be associated with a mesoscale feature not revealed in routine synoptic analyses. The upward motions below about 5 km at 2100 UTC are associated with the surface frontal passage. These features of upward motion call attention to the rich variability of vertical motions on the mesoscale. Nevertheless, it is noteworthy that, despite the mesoscale variability, the 6-h mean vertical velocity appears to be related to the large-scale flow.

In the second spring case, 1200 UTC 8 March 1990 (Fig. 1), the synoptic weather map shows a warm front approaching Flatland from the south. There was strong warm-air advection throughout the lower troposphere over Illinois ahead of the warm front. Also, there was positive vorticity advection over Illinois at 500 hPa ahead of a short-wave trough advancing from Missouri. These conditions imply upward vertical motions in synoptic-scale systems. Further, upward motion is implied by the moderate rain around Flatland shown in the surface weather reports and the weather radar summary analysis (not shown) at this time.

Upward motion is indicated by all indirect methods on 8 March 1990 (Fig. 2). Results from the kinematic method based on a triangle of radiosonde stations show the largest values of vertical motions. The NMC-based results have smaller amplitudes, likely due to the effects of smoothing in the gridded analyses.

Six-hourly mean vertical velocities observed by the Flatland radar at 1200–1800 UTC 8 March 1990 show upward motion from about 4 to 8 km. Although the magnitude is slightly less than that of the indirect computations, we note that individual hourly means range up to 15 cm s⁻¹ at these altitudes. The strong downward motion below 4 km was due to precipitation contamination of the Doppler spectrum and will be discussed more below. Heavy rain showers over Flatland before about 1200 UTC apparently influenced the Doppler spectra as high as 6 km then.

Results for the autumn cases are similar to the spring cases. On 4 October 1990 a large dome of high pressure moved over the central plains (Fig. 1). The vertical motions computed by all indirect methods were downward throughout the midtroposphere (Fig. 4). The 6-h means at each level of the radar observations nearly all fall within the envelope of values from the indirect methods. The observed vertical velocities are relatively small at low altitudes, but above about 5 km they agree closely with the estimates from the kinematic method applied to a triangle of radiosonde stations.

On 7 October, a vigorous cold front passed Flatland at about 1300 UTC (Fig. 1). Frontal passage was preceded by moderate rains for several hours. All methods
of indirect computations of vertical motions valid at 1200 UTC gave upward velocities in this case (Fig. 4), with largest estimates from the kinematic method applied to a triangle of radiosonde sites. The radar data in this case are strongly influenced by the precipitation below about 6 km as discussed next.

Figure 5 gives the time–height section of hourly mean vertical velocities from the Flatland radar on 7 October. The results show upward motion at a few centimeters per second below 4 km at 0200–0600 UTC, followed by strong upward motion above 5 km at 0600–1000 UTC, well ahead of the advancing cold front but before the moderate rain started. Note that this particular event occurs between the routine sounding times and could not be found by analyses of routine data. Furthermore, its time scale is only a few hours, implying that its spatial scale is in the mesoscale range not sampled by the rawinsonde balloon network. The strong downward motions from about 2 to 6 km and from 0600 to 1400 UTC, with particularly large values from 0900 to 1200 UTC, are due to precipitation contamination of the Doppler spectrum. The sudden onset and end of the precipitation echoes is clearly seen in the time series of individual observations given in Fig. 6.

Many of the Doppler spectra during this period show two peaks below about 5 km, as illustrated in Fig. 7. One peak represents the air motion and the other is...
due to radar scattering from the hydrometeors. Precipitation effects have been noticed before in VHF observations (Gage 1990), but it has not been widely appreciated that they can become dominant for VHF systems in moderate or heavy precipitation. In an effort to generalize the results in Fig. 6, we examined the daily charts similar to Fig. 6 for each day of February–March and September–October 1990. Periods of large radar-observed downward motion (over 1 m s\(^{-1}\)) below 6 km and lasting for over an hour were found on 7 days in spring and 12 days in autumn; precipitation was reported at the Champaign airport during, or within an hour of, each of these cases. This correlation suggests that we can attribute the large downward-motion observations to precipitation contamination. Thus, when there is precipitation, the vertical velocity measurements from VHF radars must be used with great caution below about 6 km. Efforts to develop an algorithm that can separate precipitation echoes from air-motion echoes have begun, but such an algorithm is not yet ready for routine application.

3. Summary

Six-hourly averages of the vertical motion observed at the Flatland radar have been used to test the hypothesis that temporal averages of radar vertical-motion observations can represent the large-scale flow. Case study comparisons of the radar data with the vertical motions from three indirect methods based on radiosonde observations generally show agreement in the extreme cases selected here. The radar data have the same algebraic sign as the estimates from indirect methods in nearly all cases, except in precipitation. Also, except in precipitation, the magnitude of the radar data fall within the envelope of values from the indirect estimates. A fourth indirect method, the adiabatic method, was found to be inconsistent with both the other computed vertical motions and the radar-observed vertical motions, and was deemed an unreliable method for use with radiosondes spaced at 12-h time intervals.

While these case study results suggest that radar data can be used to estimate the vertical motion associated with large-scale systems under some conditions, it is important to note that we also find that the 6-h mean vertical motion seen by the radar are still influenced by mesoscale structure. This structure is not resolved by conventional data and analyses. This complicates the comparisons, but since mesoscale processes play a significant role in the dynamics of synoptic-scale systems, future analysis and forecasting schemes should benefit from the full resolution of these features.

Finally, there is clear evidence that precipitation contamination must be taken into account during analyses of radar spectra taken at 50 MHz (lower VHF). From these few cases it is not possible to comment on the relative importance of factors such as in-
tensity of precipitation or liquid versus frozen water substance. A future study will address these factors and will investigate algorithms to separate the air motion echoes from precipitation echoes.

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REFERENCES


