Measurement of Synoptic-Scale Vertical Velocities by Two Nearby VHF Doppler Radars in Very Flat Terrain

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(Manuscript received 1 April 1992, in final form 21 January 1993)

ABSTRACT

An experimental field campaign to measure synoptic-scale vertical velocities was conducted from 5 to 11 January 1991 in the Urbana–Champaign, Illinois, region, which is in very flat terrain far from mountains. Both the Flatland and the Urbana wind-profiling radars, which are separated by 23.1 km, participated in the campaign. Meteorological sounding balloons were also launched from the Flatland Observatory site. In this study, time averages were compared of the vertical wind velocity measured directly by both radars in order to help verify the capability of wind-profiling radars to measure synoptic-scale vertical velocities. This comparison, of course, also provides an opportunity to evaluate the performance of both radars.

The variance of the vertical velocity observed by the Flatland radar has been previously shown to be dominated by short-period fluctuations with most of the variance occurring at periods less than 6 h. Also, since March 1987 when the Flatland radar began operating nearly continuously, the vertical velocity measurements showed a nearly constant downward mean value of several centimeters per second in the troposphere. After bandpass filtering, the time-series measurements of vertical velocity to obtain 6-h and 1-day means, the filtered signal is compared to similar measurements made by the newly constructed Urbana radar. Both the 6-h and 1-day time averages of vertical velocity measured by the radars displayed large variations in time and height. Variations of 10–15 cm s⁻¹ occurred frequently, which are considerably larger than the expected measurement error. Good to excellent agreement is generally found in the shape of height profiles measured by the two radars. These results suggest that wind-profiling radars located in very flat terrain are capable of measuring synoptic-scale vertical velocity profiles with useful precision.

1. Introduction

With the development of wind-profiling (also called clear-air Doppler or MST) radar technology by Woodman and Guillen (1974) and Green et al. (1975), the first routine measurements of the vertical velocity w with a time resolution on the order of a minute became possible. By chance, however, all the early wind profilers were located in or near mountains where orographic effects could dominate w measurements, thus frustrating the early studies of w and its variation due to meteorological effects (Nastrom et al. 1985; Larsen et al. 1988; Sato 1990). To minimize topographic effects, we have built VHF radars in very flat terrain near Urbana–Champaign, Illinois. (The Flatland and the Urbana radars began operation in March 1987 and January 1991, respectively.) Indeed, the Flatland w data show no evidence of orographic effects, which contrasts remarkably with data from stations located in rough terrain. For example, early results have shown that the w variations are much smaller over flat terrain and that they are associated with meteorological events (Green et al. 1988). In fact, Nastrom et al. (1990a) found that every episode of enhanced variance of w from March 1987 through May 1988 observed at Flatland was associated directly with a meteorological event, whereas at stations in or near rough terrain the meteorological events are usually overwhelmed by orographic effects.
(Nastrom et al. 1985; Larsen et al. 1988; Sato 1990). Further, VanZandt et al. (1991) found that the behavior of the spectrum of $w$ observed by the Flatland radar during windy conditions is very different from that observed at mountain locations (e.g., Ecklund et al. 1985).

Because of the importance of mesoscale and synoptic-scale vertical motion to meteorological forecasting and dynamic processes, it is important to test and evaluate the capability of these radars to measure it in flat terrain. Although the analysis of the variation of $w$ is considerably simplified by the absence of orographic effects in the Flatland data, the variance is still dominated by small-scale motions (e.g., VanZandt et al. 1991), and unfortunately there is no direct method to verify mesoscale and synoptic-scale $w$ averages, likely related to the dynamical flow, can be measured by wind-profiling radars that are located in flat terrain.

2. Data

The Flatland (Warnock et al. 1993) and Urbana (Franke et al. 1992) wind-profiling radars operate at 49.80 and 40.475 MHz, respectively. They are located in very flat terrain far from mountains near Urbana-Champaign, Illinois, separated by 23.1 km on a northeast–southwest line. From 5 to 11 January 1991, both radars measured profiles of $w$ versus height with 0.75-km range resolution, and a complete dataset was obtained over the altitude range from 3.50 to 14.75 km MSL. A summary of the radar parameters used in this study is given in Table 1. The radars at Flatland and Urbana made measurements every 108 and 150 s, respectively. Their sampling procedures, however, were quite different. The Flatland system took data from the vertical beam for about 20 of the total 108 s, and the rest of the time was used to sample the oblique antenna beams and record the data. During the 150-s Urbana measurement interval, four power spectra were taken with the vertical beam, and the median of the four spectra was analyzed and recorded. The height of the measurements may not be identical in the two systems, with the Flatland heights about 125 m higher than Urbana’s. Since this is smaller than the height calibration and less than 20% of the height resolution, we have plotted the data from both radars at identical heights in order to facilitate the comparisons.

Although we are primarily concerned with time scales from 6 h to 1 day in this comparison, we must also consider both longer and shorter time scales to bandpass filter the data properly. Both Figs. 1 and 2 demonstrate features of three separate time regimes in the dataset. Figure 1 is a time series of $w$ at 5 km measured by the Flatland radar during the campaign; each measurement is a point on the figure, and the values range from −72.5 to 62.9 cm s$^{-1}$ with a mean value of −6.24 cm s$^{-1}$. This dataset has been edited by first eliminating physically unrealistic values (i.e., values larger than ±3 m s$^{-1}$) and then removing values greater than plus or minus three standard deviations $\sigma$ from the median of the sample for each height. This standard and simple editing procedure removes effectively most echoes from airplanes, meteors, and man-made interference. Figure 2 is a histogram of the $w$ measurements shown in Fig. 1. The solid curve in Fig. 2 is the best-fitting Gaussian curve, which is a good fit to the histogram. The mean and median of the distribution are −6.24 and −6.19 cm s$^{-1}$, respectively, and the center of the Gaussian is −5.80 cm s$^{-1}$, which agrees quite well with the mean and median.

![Figure 1](image_url)

**Fig. 1.** Time series of $w$ at 5 km measured by the Flatland radar from 5 to 11 January 1991. The points are the individual measurements. The solid line is the 6-h means of the points, and the dashed lines are the 6-h means plus or minus one standard deviation.

<table>
<thead>
<tr>
<th>Location</th>
<th>Flatland radar</th>
<th>Urbana radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude (°N)</td>
<td>40.05</td>
<td>40.15</td>
</tr>
<tr>
<td>Longitude (°W)</td>
<td>88.38</td>
<td>88.15</td>
</tr>
<tr>
<td>Altitude (m MSL)</td>
<td>212</td>
<td>226</td>
</tr>
</tbody>
</table>

**Table 1.** Radar parameters.

<table>
<thead>
<tr>
<th>Operational parameters</th>
<th>Flatland radar</th>
<th>Urbana radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>49.80</td>
<td>40.475</td>
</tr>
<tr>
<td>Wavelength (m)</td>
<td>6.02</td>
<td>7.41</td>
</tr>
<tr>
<td>Peak power (kW)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Pulse length (m)</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>Height resolution (m)</td>
<td>750</td>
<td>750</td>
</tr>
<tr>
<td>Lowest height (km MSL)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Highest height (km MSL)</td>
<td>16.25</td>
<td>16.25</td>
</tr>
<tr>
<td>Velocity resolution (cm s$^{-1}$)</td>
<td>15.6</td>
<td>11.6</td>
</tr>
<tr>
<td>Unambiguous velocity interval (m s$^{-1}$)</td>
<td>±20</td>
<td>±7.41</td>
</tr>
</tbody>
</table>
An important feature of the $w$ data shown by Figs. 1 and 2 is its very large variance. The variance of $w$ measured by the Flatland radar has been studied in detail by VanZandt et al. (1991). They studied the variance spectrum from periods of 5 min to 45 h using an entire year of data, and found that the spectrum consisted of two regimes with a transition near 6 h. The short-period regime contains almost all the variance, and they further showed that this regime is consistent with a gravity-wave spectrum that has been Doppler shifted by the background wind. The variance of the regime from 6 to 45 h is usually considered to be due to weather systems at mesoscales and synoptic scales. The variance of the data shown in Fig. 1 at a scale is seen more clearly when we divide it into periods of 6-h length and calculate the mean ($\bar{w}$) and $\sigma$ of each period. The solid center curve in Fig. 1 is $\bar{w}$, and the dashed upper and lower curves are the mean plus or minus a standard deviation. Note that the 6-h $\bar{w}$ signal is measurable and has a significant variability. The difference between the minimum and maximum means is 20.7 cm s$^{-1}$, and the largest change in 6 h is 15.3 cm s$^{-1}$. Even larger variations are observed in the 6-h $\bar{w}$ height profiles; these are given and discussed in the next section.

A third, much longer, important time scale must also be considered. Since the Flatland radar began operating in March 1987, its nearly continuous measurements of $w$ for more than five years have shown downward mean motions of several centimeters per second in the middle and upper troposphere (Nastrom et al. 1994; Clark et al. 1993). For example, Nastrom et al. found a $\bar{w}$ of about $-4.7$ cm s$^{-1}$ over the height range of 3.7–9.0 km for January 1988. A very similar pattern of descent was observed by Nastrom et al. (1994) using the 50-MHz radar located at Liberal, Kansas, which operated during the two months of the PRE-STORM experiment from 6 May to 30 June 1985. Also, a similar pattern with $\bar{w}$ between 10 and 20 cm s$^{-1}$ is seen near the jet stream by the MU radar (Fukao et al. 1991). The studies by Nastrom et al. and Clark et al. discuss many possible causes for the descent in the troposphere, but they conclude that known instrumental effects such as a small tilt in the antenna beam are not consistent with the observations. Not surprisingly, this descent in the troposphere can be clearly seen in Figs. 1 and 2. The histogram of Fig. 2 shows that $\bar{w}$ observed by the Flatland radar is a downward shift from zero of the entire distribution of $w$, and not due to an asymmetry in the distribution.

Thus, to study scales from hours to days, we must bandpass filter the data to reduce sufficiently both the shorter-period gravity-wave effects and the long-term station mean. A standard method to filter out the gravity-wave contributions is to simply average the data over time. In this study we use both 6-h and 1-day means. To filter out the long-term station mean, while retaining the height variability of the data, we simply shift each height profile by the negative of its station mean.

3. Results

The time series of $w$ were averaged at each altitude over three different time periods: over the entire campaign period of 5.25 days (1800 UTC 5 January to 0000 UTC 11 January 1991); over five 1-day periods; and over 21 6-h periods. During the campaign there were times when one or the other radar was down for routine maintenance or to change the data recording media. In addition, there were times when the signal-to-noise ratio at some heights is too small to measure $w$. When there was a time gap in the time series for a given height for either radar, we removed the corresponding data for that height from the time series of the other radar in order to ensure a valid comparison. During a few of the 1-day and 6-h periods, the combination of down time and low signal to noise at some heights reduced the number of valid records below the number required to make a useful mean. Thus, in the Flatland–Urbana comparison figures shown below, we have required that one-fifth or one-third of the records be valid in order to calculate a mean for the 1-day or 6-h periods, respectively. Otherwise the mean for that height is not calculated.

To compare the variability with height of $\bar{w}$ between the two radars for the 6-h and 1-day periods, we have filtered out the long-term station mean from the Flatland data as described at the end of the previous section. In practice, this station mean is approximately equal to $\bar{w}$ measured during this campaign. Since these are the first measurements of the Urbana system, there is no known long-term mean of the Urbana data. Thus,
for consistency, we have simply shifted the Flatland or Urbana data by the negative of their mean during the campaign, +5 cm s$^{-1}$ or −2 cm s$^{-1}$, respectively. These shifts are, of course, independent of height so they do not affect the height variability or correlation between the two profiles, but simply allow a direct comparison of the variability of $\bar{w}$ with height. The station means and their differences are not yet understood; the long-term Flatland mean, however, is examined in detail by Nastrom et al. (1994) and Clark et al. (1993).

Figure 3 is a summary for the entire 5.25 days of the campaign. Figure 3a compares the height variability of $\bar{w}$ measured by the two radars. In this and in all the following comparison figures, the Flatland and Urbana data are denoted by solid and dashed curves, respectively. The agreement in shape between the two profiles is generally excellent except at the lowest two heights, below 5 km. The major feature of both profiles is a decrease in $\bar{w}$ from 6.50 to 8.75 km of 5.6 and 4.3 cm s$^{-1}$ for the Flatland and Urbana datasets, respectively, followed by an increase in $\bar{w}$ from 8.75 to 11.00 km of 5.8 and 5.7 cm s$^{-1}$, respectively. At heights below 5 km, Pauley et al. (1994) and Nastrom et al. (1994) have found that precipitation effects produce negative values. During this campaign, there were three days of light snow and freezing rain, so that the values below 5 km are thought to be contaminated by precipitation effects. The correlation coefficient between the two profiles is 0.66 for the entire height range, whereas the correlation coefficient is 0.88 for the partial profile from 5 km and above. Nastrom et al. (1990b) have estimated the standard error of the mean for 6-h means of the Flatland data to be 2 cm s$^{-1}$. Extrapolating this value to the 5.25-day campaign period yields an error of 0.5
cm s\(^{-1}\) so that the variations shown in Fig. 3a are much larger than the expected error and are, therefore, statistically significant.

Figure 3b shows the \(\sigma\) of the \(w\) distributions observed during the campaign. Note that the \(\sigma\) of the Flatland distribution is almost twice as large as that for the Urbana distribution, due to the different sampling and data analysis procedures used by the two systems. At Urbana, the median of each set of four power spectra is taken to produce a smoothed spectrum; that is, for each point of the spectrum, the minimum and maximum values are removed and the central two values are averaged. This process should decrease \(\sigma\) by a factor somewhat less than 2, consistent with the observed difference.

Figure 3c shows the mean signal-to-noise ratio profile observed at Flatland for the campaign. The center curve is the median of the distribution, and the dashed curves are the upper and lower quartiles of the distribution; thus, the central half of the data lies between the two dashed curves. In the height range between 9 and 11 km and above 14 km, the signal-to-noise ratio is low, and many of the records could not be analyzed making the curve an upper limit; furthermore, for the records that are analyzed, the determination of \(w\) is less accurate. The height of the tropopause determined by the World Meteorological Organization (WMO) operational definition from the upper-air data observed by the balloon instruments launched from the Flatland site ranged from 10.6 to 11.6 km during the campaign. In the height range at and above the tropopause, the radar reflectivity of the atmosphere is strongly anisotropic (i.e., aspect sensitive), and the \(w\) measurements are less certain because the reflecting layers may be slightly tilted, so that the \(w\) measurements could be contaminated by the horizontal wind (e.g., Rottger et al. 1990; Palmer et al. 1991; Larsen and Rottger 1991; Van Baelen et al. 1991). For these reasons, the \(w\) measurements from 9 to 12 km are less accurate than at other heights.

Figure 4 shows five comparisons between 1-day averages of \(w\) measured by the two radars. The standard error of the mean is about 1.0 cm s\(^{-1}\), which is much smaller than the variations shown in Fig. 4. In Fig. 4a, the agreement between the two radars is poor in the middle troposphere and excellent in the stratosphere. The gap in the upper troposphere is due to an insufficient number of valid records because of the low signal-to-noise ratio in this height region. In the next four days (Figs. 4b–e) the agreement is good to excellent with the worst agreement at heights below 5 km where the precipitation effects are important. Otherwise the agreement is usually excellent. A striking feature of some of the profiles is the appearance of wavelike structure over part of the height range with a vertical wavelength of 3–4 km. The amplitude and shape of many of these features are similar in both the Flatland and Urbana profiles, particularly in Fig. 4c.

Figure 5 shows the comparison for five 6-h periods. In the first period (Fig. 5a), a wavelike structure dominates the entire height range of both profiles, and the agreement in the wave shape observed by the two radars is excellent. The vertical wavelength of the structure is about 4 km and its amplitude is between 10 and 15 cm s\(^{-1}\) in the upper troposphere and lower stratosphere. In the next two periods (Fig. 5b and 5c) however, the wavelike structure is not visible. In Fig. 5d, 18 h later than Fig. 5c, a similar wavelike structure is clearly visible again. One of the radars was down for maintenance during most of the next 6-h period, and the pattern had disappeared in the following period shown in Fig. 5e.

It is instructive to study the synoptic situation during the time Fig. 5d and 5e were taken. A cold front passed Flatland at the surface at about 0800 UTC 9 January 1991. The frontal passage was accompanied by freezing drizzle and snow flurries and was followed by widespread fog. Aloft, there was cold-air advection throughout the troposphere ahead of an eastward-moving cold-core trough. For example, the 250-hPa analyses at 1200 UTC 9 January and 0000 UTC 10 January 1991 (Fig. 6) show a sharp temperature decrease toward the west between Illinois and Nebraska. Such a temperature gradient on a constant-pressure surface implies the isentropic surfaces slope toward the east over Illinois. In the absence of diabatic heating, the air parcels follow isentropic surfaces and thus may be expected to show downward motion over Flatland. Indeed, the adiabatic method applied to radiosonde data at Peoria, Illinois (about 120 km northwest of Flatland), gives downward vertical velocity of about 6 cm s\(^{-1}\) at 250 hPa (about 10.3-km altitude) at both 1200 UTC 9 January and 0000 UTC 10 January. The local vertical velocities seen in Fig. 5e compare remarkably well with this area-average estimate. Several other comparisons between \(w\) measured by the Flatland radar and indirect methods of estimating \(w\) are given by Nastrom et al. (1994) and Nastrom and Warnock (1994).

4. Summary and conclusions

It is constructive to consider the time series of radar \(w\) measurements as three time-scale regimes. The shortest regime includes scales from the measurement time of a few minutes to about 6 h. This regime contains almost all the variance and is consistent with a gravity-wave spectrum that has been Doppler shifted by the background wind (VanZandt et al. 1991). The longest regime is the long-term station mean. A good estimate of this mean is the mean of the 5.25 day campaign, which is about \(-5\) or \(+2\) cm s\(^{-1}\) for the Flatland and Urbana radars, respectively. A middle regime of scales from 6 h to 1 day is usually thought to be related to mesoscale and synoptic-scale flow. Indeed, after bandpass filtering the \(w\) time series measured by the Flatland and Urbana radars to 6-h and 1-day periods, we find
FIG. 4. Profiles of 1-day-mean vertical velocity. The Flatland data are the solid lines and the Urbana data are the dashed lines. The Flatland profile has been shifted by +5 cm s$^{-1}$ and the Urbana profile by -2 cm s$^{-1}$ as described in text. (a) 6 January 1991, (b) 7 January 1991, (c) 8 January 1991, (d) 9 January 1991, (e) 10 January 1991.
FIG. 5. Profiles of 6-h-mean vertical velocity. The Flatland data are the solid lines and the Urbana data are the dashed lines. The Flatland profile has been shifted by +5 cm s$^{-1}$ and the Urbana profile by -2 cm s$^{-1}$ as described in text. All times in UTC: (a) 0000–0600 8 January 1991, (b) 0600–1200 8 January 1991, (c) 1200–1800 8 January 1991, (d) 0600–1200 9 January 1991, (e) 1800–2400 9 January 1991.
generally good to excellent agreement between the height profiles of the two radars.

The agreement in shape of the profiles between Flatland and Urbana measurements of \( \bar{w} \) is excellent for the 5.25-day average, good to excellent for the 1-day averages, and poor to excellent for the 6-h averages. The agreement is poorest at heights below 5 km, where Pauley et al. (1994) and Nastrom et al. (1994) have found that precipitation effects may dominate the radar measurements. Since there were several episodes of snow and freezing rain during this campaign, the radar measurements may not be reliable below 5 km during precipitation. Most of the profiles display large variations in \( \bar{w} \) with height of 10–15 cm s\(^{-1}\), sometimes displaying a wavelike pattern with vertical wavelengths of 3–4 km. Since both radars observe the patterns simultaneously with similar amplitudes, they are clearly observing the same atmospheric features.

This agreement between measurements of \( \bar{w} \) by the two nearby radars supports the hypothesis that wind profiling radars in flat terrain are capable of measuring variations of synoptic-scale features of \( w \) under certain conditions. This capability should have a major impact on the design and siting of future radar systems and on the use of their data for meteorological forecasting and research. Therefore, many more comparison studies should be made under a wide variety of meteorological conditions to evaluate this measurement technique thoroughly.

Acknowledgments. We are happy to thank S. W. Henson of the Digital Computer Laboratory of the University of Illinois for his help in maintaining and operating the Flatland radar. The Flatland radar is located on the Bondville Field Site of the Department of Electrical and Computer Engineering of the University of Illinois. This material is based on work partially supported by the National Science Foundation under Grants ATM-8512513 and ATM-9020955.

REFERENCES


FEBRUARY 1994


