Errors in Mean Vertical Velocities Measured by Boundary Layer Wind Profilers

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ABSTRACT

The accuracy of vertical velocities measured by UHF wind-profiling radars has been a matter of discussion for some time. This paper shows that there are significant errors in mean vertical velocities measured by the vertical beam of 915-MHz wind profilers. The erroneous velocities are 0.1–0.3 m s^{-1} downward in daytime convective boundary layers over two sites, flat farmland in Illinois and rolling forest in Wisconsin. Velocities at night are not affected, and different days have different erroneous velocities. The directly measured velocities are compared to vertical velocities calculated from the divergence of the horizontal wind to show that they are indeed in error. The erroneous velocities are not caused by detectable rain, by an error in the beam pointing direction, or by the skewness of the vertical velocity distribution. They are probably due to small targets (particulate scatterers) that have a small fall velocity and are detected by the radar. An online algorithm for removing intermittent contamination reduces the error, but does not eliminate it. The fluctuating component of the velocity is not affected by these errors since it is much larger in magnitude.

1. Introduction

Boundary layer wind profilers are in common use for long-term and campaign-style studies of atmospheric dynamics and chemistry. Researchers have noted that there appears to be a bias in the average vertical velocities measured by these profilers. This paper shows that the bias exists at two rather different sites, describes its characteristics, and explains the most probable causes thereof.

The most common type of boundary layer wind profiler, developed at the NOAA Aeronomy Laboratory (Carter et al. 1995; Ecklund et al. 1988), operates at 915 MHz. Unlike the more familiar weather radars, the profiler is designed to respond to fluctuations of the refractive index in the clear air, although it is also sensitive to targets such as hydrometeors, insects, and birds. The findings in this paper also apply to other types of profilers operating in roughly the same frequency range. Boundary layer profilers operate by sampling the Doppler velocity of the air along three to five beam directions, usually a vertical beam and two or four beams pointed 15°–20° from vertical. Each beam is sampled for 30–60 s. The sample volume depends on the selected vertical resolution, the beam width (inversely related to antenna size), the range, and the mean wind speed, but is typically 10^6 m^3. The vertical beam is used to detect and remove the effects of precipitation, but it would be very useful if the velocity it measures were the accurate vertical velocity of the atmosphere above the profiler. Unfortunately, this is not the case for mean velocities.

In convective boundary layers, instantaneous vertical velocities on the scale directly measured by the profiler are quite large, 2–3 m s^{-1} being usual. In contrast, mean vertical velocities on the synoptic scale are two orders of magnitude smaller, except during transient events such as storms or frontal passages. There is a roughly linear relationship between spatial or temporal scale and mean velocity. On any spatial scale, the mean vertical velocity over a sufficiently long time period should be very small unless the measurement is in a persistently anomalous location.

Data from two locations are shown here. The Flatland Atmospheric Observatory (Flatland or FAO) is located in very flat terrain southwest of Champaign–Urbana, Illinois. This site is also known as the University of Illinois Bondville field site. The surrounding land is flat to within 5 m for several kilometers. Corn (maize) and soybeans are grown in the area, in patches varying from 1/4 to 1 mile (0.4–1.6 km) on a side, with roughly equal proportions of each crop. In contrast, the Park Falls, Wisconsin, site was in a clearing in rolling land forested with mixed hardwood and deciduous trees and a considerable proportion of wetlands. The terrain elevation within several kilometers of the site varied by up to approximately 50 m.

Both profilers were operated at 60-m vertical resolution (pulse coded) with a minimum height of 150 m AGL. Six beam positions, four oblique beams in two coplanar pairs and two vertical beams of orthogonal

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polarizations, were used. The dwell time on each beam was approximately 25 s. Each cycle also included a single vertical beam measurement at 500-m resolution to detect rain at altitudes up to 12 km. The maximum height of the 60-m resolution measurements varies from 1.5 to 3 km depending on atmospheric conditions, especially humidity, but is always sufficient to cover the convective boundary layer in the summer. The wind measurements, when averaged over 30 min, have accuracy better than 1 m s^{-1} (Angevine and MacPherson 1995). The only significant difference between the FAO and Park Falls profilers was the antenna. FAO has a nine-panel (3 m $\times$ 3 m) antenna with a two-way half-power full beam width of 4°. Park Falls had a more usual four-panel (2 m $\times$ 2 m) antenna with a beam width of 6°. The direct vertical velocity measurements from FAO will be compared with velocities calculated from the divergence of the horizontal wind measured by a triangle of profilers, one of which was the FAO profiler.

2. Data processing

Before profiler data can be used, they must be subjected to quality control (''cleaning'') to remove contamination from aircraft, radio frequency interference, birds, precipitation, and other sources. The statistical filtering technique described by Angevine et al. (1993) was applied to the data presented here. In brief, this technique discards data where any of the three moments (signal-to-noise ratio, velocity, and spectral width) fall outside two or three standard deviations (depending on the moment) of each 1-h time series. There is also a floor of signal-to-noise ratio below which all data are discarded. This technique discards obvious outliers while preserving turbulence information. Only a few points are discarded in a normal hour within the convective boundary layer. Hours with more than 12 outliers (out of approximately 24) were discarded.

The data presented here were also screened for rain by examining the reflectivity and vertical velocity for rain signatures (large reflectivities or strong downward velocities covering many heights). Because the real vertical velocities in convective boundary layers are large, simple filtering of vertical velocities to remove rain as suggested by Ralph (1995) cannot be used.

The on-line processing of these data was done with both normal spectral averaging and the statistical averaging technique designed to remove returns from birds (Merritt 1995), referred to as the ''bird algorithm.''

3. Results and discussion

The vertical velocity directly measured by the profiler has a distinct diurnal cycle, as shown in Fig. 1, where the averages of all data at each hour and over the layer from 200 to 1000 m AGL are plotted. For FAO the data are from 39 days in August and September 1995, and for Park Falls the data are from 44 days in June–October

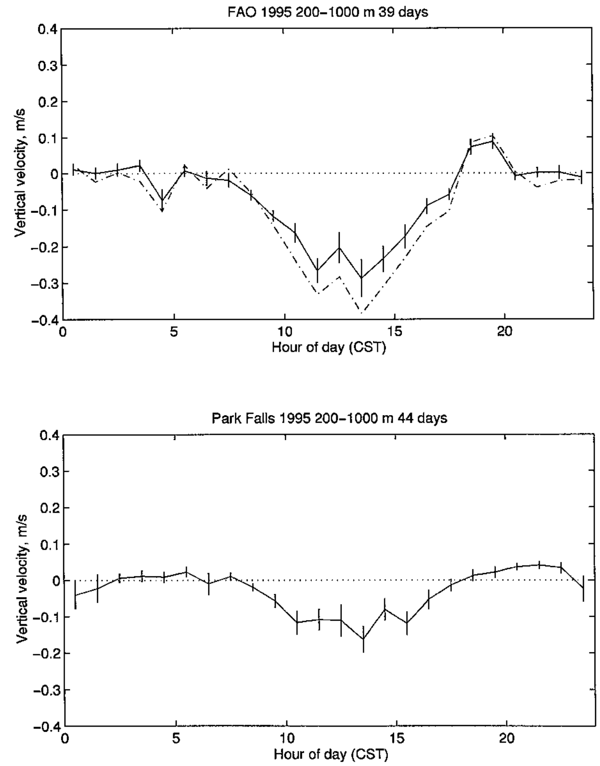

FIG. 1. Composite diurnal behavior of vertical velocity measured by the profiler vertical beam. Solid lines are data processed with the bird algorithm, and the dash–dot line is data processed by simple spectral averaging. Velocities are also averaged over the layer from 200 to 1000 m AGL. Bars are the standard error of the mean for each hour. (a) Average over 39 days in August and September 1995 at the Flatland Atmospheric Observatory in Illinois. At least 27 days are included in each hourly average. (b) Average over 44 days in June–October 1995 at Park Falls, Wisconsin. All 44 days are represented in each hourly average.

1995. There is a strong downward velocity in the middle of the day but no significant departure from the expected value of zero at night. The bird algorithm removes a small portion of the error in the data from FAO (Fig. 1a). The figure indicates that the phenomenon causing the erroneous vertical velocities takes place during the day only. There is some possibility of ground clutter contamination of the observed velocities in this height range, particularly at the Park Falls site. Ground clutter tends to bias the observed velocities toward zero, so the data shown here may be less negative than they would be in the absence of clutter.

Averages of all data for each day (all 24 h) are plotted in Fig. 2. The same days are used as in Fig. 1. Some days are not included, usually because rain was present on those days. Both datasets have large variations in vertical velocity from day to day. The measured velocities at FAO are almost always downward (negative). At Park Falls, 10 of the 44 days have significantly upward (positive) velocities, but these are always small.

A triangle of profilers, including the FAO profiler and two provided by the National Center for Atmospheric

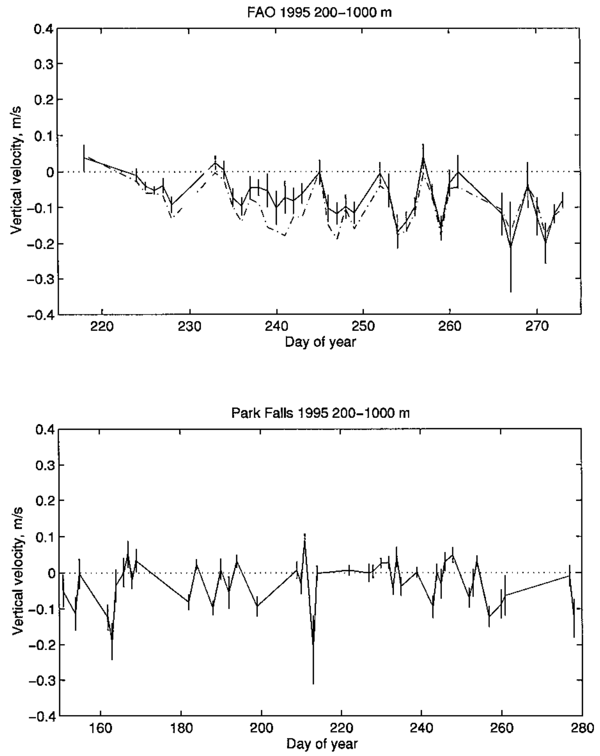

FIG. 2. Daily averages of vertical velocity measured by the profiler vertical beam. Data and notation are as in Fig. 1. At least 12 h are represented in each daily average.

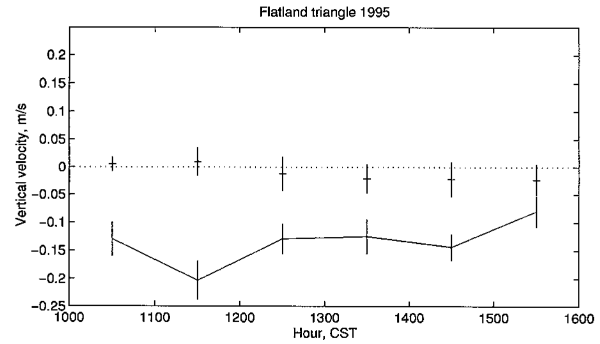

FIG. 3. Vertical velocity measured by the FAO profiler vertical beam (solid) compared with vertical velocity calculated from the divergence of the horizontal wind measured by a triangle of wind profilers including FAO (crosses). Bars are the standard error of the mean for each hour. Between 18 and 21 days are included in each hourly average. The vertical beam measurement is an average over three range gates.

Research, was operated during August and September 1995. The triangle was nearly equilateral with sides 5.5–7 km in length. The true vertical velocity at the boundary layer top z_i over the triangle was calculated by integrating the divergence of the horizontal wind from the surface to the boundary layer top measured by the profiler (Angevine et al. 1994a). The divergence at each height (radar range gate) was calculated by the formula of Davies-Jones [1993, Eq. (4)] using 1-h averages of winds from each of the three stations. The surface divergence was also calculated from 10-m anemometer measurements at each site. Vertical velocity at each height is the negative of the divergence integrated from the surface to that height. Since the first range gate is 120–180 m, some assumption must be made about the divergence between the surface and the first gate. For the results shown below, the assumption was that the divergence profile is linear between 10 and 120 m. The results are not sensitive to this assumption. In calculating the vertical velocity, no more than two range gates of bad data, as defined by the quality control algorithms above, were allowed, and the divergence at those heights was set to zero. The divergence at any range gate was limited to $\pm 3 \times 10^{-4}$, a threshold chosen subjectively from an examination of many divergence profiles. This limiting affected only a few hours of data and had only a small effect on the overall results.

Figure 3 shows a comparison between the vertical velocities measured by the triangle and the velocities directly measured by the profiler vertical beam. Only daytime (1000–1600 CST) results are shown. Fewer days are included (26) than in the earlier figures, since the constraints for good measurements by the triangle are more severe. The same days are used for the vertical beam measurement enabling a direct comparison to be made. The vertical velocities calculated from the divergence are not significantly different from zero. The overall mean is -0.005 m s^{-1} with a standard error of 0.01 m s^{-1}. In contrast, the direct measurement always differs from zero and is between -0.08 and -0.20 m s^{-1}. This makes clear that the velocities directly measured by the vertical beam are in fact erroneous.

The behavior of the directly measured vertical velocity with wind speed is shown in Fig. 4a, where data are grouped into wind speed bins of 2 m s^{-1} width. The strongest downward velocities occur in light winds (2–7 m s^{-1}). All hours of the day are included, and there is, of course, a strong correlation between time of day and wind speed, stronger winds occurring most often at night. In Fig. 4b, the data are averaged over quadrants of wind direction. The average velocity is downward for all wind directions except for a small upward velocity for the northeast quadrant at Park Falls. The behavior with respect to wind direction shows that an error in the pointing direction of the beam is not the cause of the erroneous velocities. If a pointing error were the cause, the measured velocity would be positive for some wind directions. Some contribution from pointing errors may be present, but it is at most 0.02–0.03 m s^{-1}, the amplitude of the variation with wind direction.

Profiles of mean directly measured vertical velocity with respect to height normalized to the boundary layer height are shown in Fig. 5. These are daytime (0800–1800 CST) data only, since the profiler can only measure boundary layer height during the day. There is a distinct profile shape at both sites, with the maximum vertical

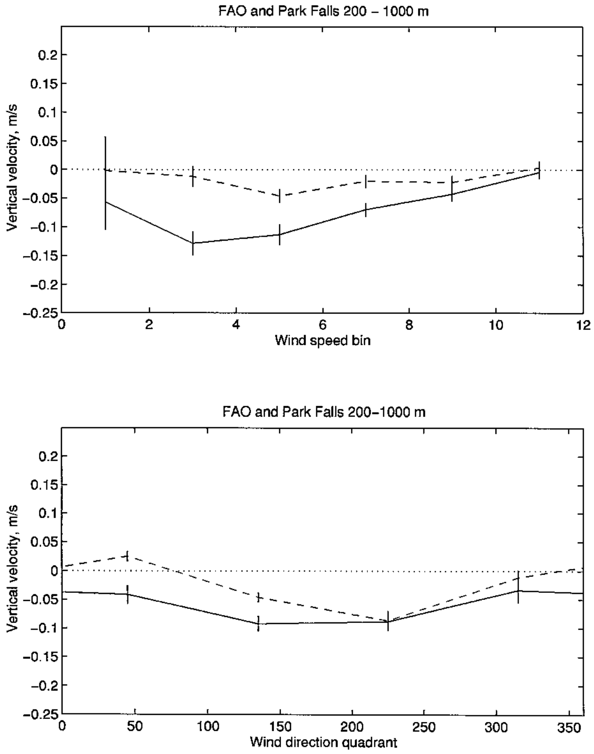

FIG. 4. Wind speed and direction dependence of vertical velocity measured by the profiler vertical beam at FAO (solid) and Park Falls (dashed). Bars are the standard error of the mean for each bin. (a) Wind speed bins 2 m s^{-1} wide. For FAO, 97–245 h of data are included in each bin except the 0–2 m s^{-1} bin, which has only 20 h. For Park Falls, 59–102 h are included in each bin except the 0–2 m s^{-1} bin, which has 8 h. (b) Quadrants of wind direction from degrees east of north (0°–90°, 90°–180°, 180°–270°, and 270°–360°). For FAO, quadrants contain 193, 178, 321, and 99 h of data, respectively. For Park Falls, quadrants contain 144, 141, 53, and 25 h of data, respectively.

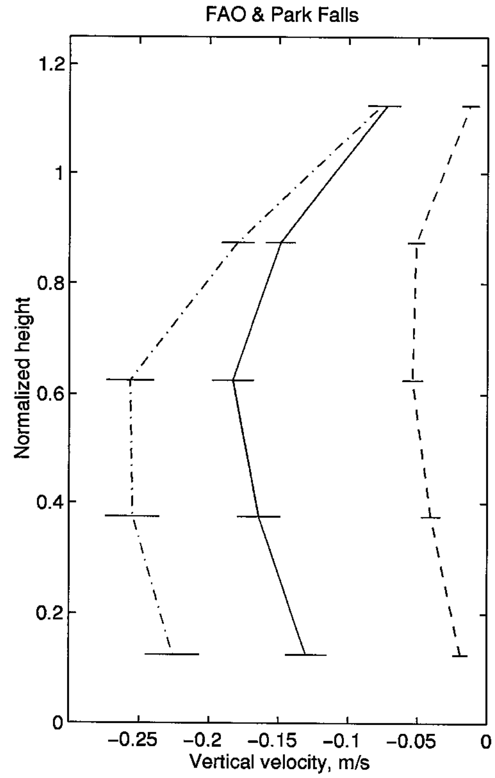

FIG. 5. Vertical velocity measured by profiler vertical beam vs height normalized to boundary layer height measured by the profiler (z/z_i). Only daytime data are included. Solid: FAO with bird algorithm. Dashed: Park Falls with bird algorithm. Dash–dot: FAO with simple spectral averaging. Bars are standard error of the mean for each normalized height bin (0–0.25z_i, 0.25z_i–0.5z_i, 0.5z_i–0.75z_i, 0.75z_i–1.0z_i, and 1.0z_i–1.25z_i).

velocity occurring in the middle of the boundary layer. The effect of the bird algorithm at FAO is very strong in the middle and lower boundary layer, eliminating nearly half of the mean velocity. This means that one-third to one-half of the error (the difference between the measured velocity and zero) is due to targets that are eliminated by the bird algorithm, that is, small numbers of strongly reflective targets.

The shapes of the profiles shown in Fig. 5 are consistent with the hypothesis that the errors might be caused by the skewness of the velocity distribution. However, a simple model shows that this is not likely to be the case. A gamma distribution with mean subtracted, skew coefficient 0.6, and standard deviation 1.0 m s^{-1} was constructed and sampled in a Monte Carlo experiment. These parameters are consistent with those observed in convective boundary layers (LeMone 1990). From this distribution, 1000 independent groups of 100 or 500 samples were taken and averaged. Each 100- or 500-sample average represents an average of the profiler data. For 100 samples, approximately 17% of the averages were less than -0.1 m s^{-1} and 33% were less than -0.05 m s^{-1}. Only 1% of the 500-sample averages were less than -0.1 m s^{-1} and 13% were less than -0.05 m s^{-1}. Assuming that this model is representative of the data shown, this means that approximately 17% of the time an average of 100 independent samples of the vertical velocity will be less than -0.1 m s^{-1}, and only 1% of the time an average of 500 independent samples will be less than -0.1 m s^{-1}.

How many independent samples are included in the data shown? This is a somewhat difficult question. The data quality control described above discards hours with fewer than 12 samples. Each of those samples is itself a 25-s average, and the samples are spaced approximately 75 s apart. This is probably not far enough apart to ensure complete independence between samples, but it seems conservative to assume that every other sample is independent in time. The data shown are also averages over multiple heights (range gates). Independence of samples in height is also difficult to quantify since it depends on the scattering mechanism and the atmospheric structure. It seems conservative, however, to assume that every third range gate (180 m) is independent. With these assumptions, each data point in Fig. 1 and Figs. 3–5 contains at least 500 independent samples. The data most likely to be problematic are in Fig. 2, where as few as 108 independent samples may be included.

It is therefore unlikely that individual points in Figs. 1 and 3–5 are due to skewness. The consistent patterns in time and height shown in these figures are even less likely than individual points to be due to the skewness since individual points are independent. In Fig. 2, there is a small but nonnegligible probability that some of the points are affected by the skew, especially at Park Falls, where the downward velocities are smaller. We cannot rule out the possibility that the profilers are sited in locations with persistent downdrafts that would make the velocity estimates dependent and invalidate the statistical analysis above. However, the terrain surrounding both sites is generally flat and uniform on the scale of the footprint of the profiler measurement at the heights considered, so there is no reason to suspect persistent circulations of the observed magnitude. It also seems quite unlikely that two sites in different terrain are both so unfortunately sited as to observe persistent downdrafts at all heights.

4. Conclusions

The data presented here show that there is a systematic error in vertical velocities measured by the vertical beam of two 915-MHz boundary layer wind profilers. That the measurements are in error is shown by their large mean magnitude as well as the contrast with vertical velocities calculated from the divergence of the horizontal winds over a 6–8-km triangle. The error occurs during the day in the convective boundary layer. The error is not due to skewness of the vertical velocity distribution, to a pointing angle error, or to detectable rain. Eliminating days with detectable rain may introduce a downward bias, since such days are more likely to have low barometric pressure and consequent upward motions on the synoptic scale, but this is not significant in the datasets, which both show zero vertical velocity at night. The effect shown here is much larger than that observed in VHF wind profiler data in the free troposphere by Nastrom and VanZandt (1996).

Multifrequency radar studies at the FAO (Ecklund et al. 1995) and other locations (Wilson et al. 1994) show that particulate scatterers are common in convective boundary layers over land. These scatterers may be insects or hydrometeors. Particulate scatterers with a small fall velocity appear to be the most likely cause of the observed errors in the mean vertical velocity. The size of the error and its distribution in time are likely to vary from site to site depending on the density and behavior of these scatterers. Particulate scatterers are apparently fewer or smaller at the Park Falls site than at the FAO.

It is important to note that the fluctuating component of the vertical velocity is much larger than the observed errors of the mean and is not likely to be affected by the errors. Measurements of the vertical velocity variance and heat flux (Angevine et al. 1993, 1994b) indicate that measurements of the fluctuating component of vertical velocity are substantially correct.

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