Wind Profiler and RASS Measurements Compared with Measurements from a 450-m-Tall Tower

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ABSTRACT

A 915-MHz boundary layer wind profiler with radio acoustic sounding system (RASS) was sited 8 km from a very tall (450 m) television transmitting tower in north-central Wisconsin during the spring, summer, and autumn of 1995. The profiler measured wind means and variances, and the RASS attachment measured virtual temperature. These quantities are compared to measurements from cup and sonic anemometers and a thermometer/hygrometer at 396 m above ground level on the tower. The precision of hour-averaged profiler winds is better than 1 m s^{-1}, and the precision of the RASS virtual temperature is better than 0.9 K. Corrections to the virtual temperature measured by the RASS are discussed, and a new virtual temperature retrieval method is proposed. Vertical velocity variance correlation is similar to a previous study, and the fact that bias is small indicates that the calculation method used is reliable.

1. Introduction

Boundary layer wind profilers operating at 915 MHz were developed at the NOAA Aeronomy Laboratory (Carter et al. 1995; Ecklund et al. 1988). These transportable systems have been deployed at a large number of meteorological and chemical campaigns, as well as in long-term studies in the Tropics. A few studies describing the precision and accuracy of wind measurements by boundary layer profilers based on comparisons with aircraft (Angevine et al. 1995) or rawinsondes (e.g., Riddle et al. 1996; Martner et al. 1993) have appeared in the literature. The precision and accuracy of radio acoustic sounding system (RASS) temperature measurements in the boundary layer have been explored by Peters and Angevine (1996) and Angevine and Ecklund (1994), again by comparison with rawinsondes. The precision and accuracy of winds from other types of profilers were addressed by Strauch et al. (1987) and Martner et al. (1993). A 50-MHz system was used for a comparison of RASS with radiosondes by Moran and Strauch (1994). Rawinsonde comparisons suffer from the usual problem that rawinsondes are very limited in their temporal and spatial coverage, describing only a single vertical profile in space and, at each height, a single instant in time. Aircraft comparisons have similar limitations, depending on the flight patterns. In this paper, we compare the profiler measurements with data from a tall television transmitting tower. Since the tower instruments operate continuously, the temporal coverage of the comparison is much better, and averaging times can be coordinated. The tower, equipped with a sonic anemometer, also allows comparison of turbulence measurements, in this case vertical velocity variance.

The tower is located in the Chequamegon National Forest near Park Falls, Wisconsin. The profiler was located about 8 km away in a clearing. The area is 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. The tower was instrumented for meteorological and climate-related chemical measurements as part of an ongoing study of regional forest–atmosphere exchanges of climate-related trace gases

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(Davis et al. 1996). Instrumentation used in this study consisted of a cup anemometer (Vaisala WAA 15A), wind vane (Vaisala WAV 15A), temperature and relative humidity sensor (Vaisala HMD 20YB), and a sonic anemometer (Applied Technologies Inc. SAT-11/3K), all at 396 m above ground level (AGL). A rain gauge was located at the base of the tower. The data from all instruments, except the sonic anemometer, were stored as 30-s averages. The sonic data were stored at 5 Hz.

The profiler was at the site from mid-May through mid-October 1995. It was operated at 60-m vertical resolution (4-bit pulse coded) with a minimum height of 150 m AGL. Six beam positions, four oblique beams consisting of two orthogonal pairs of coplanar beams and two vertical beams of orthogonal polarizations, were used. The dwell time on each beam was approximately 45 s. Each cycle also included a single vertical beam measurement at 500-m resolution to detect rain at altitudes up to 12 km. A full cycle took approximately 315 s and produced two estimates of each wind component. The maximum height of the 60-m resolution measurements varied from 1.5 to 3 km depending on atmospheric conditions, especially humidity, but was always sufficient to cover the convective boundary layer in the summer. The profiler antenna was the usual four-panel (2 m $\times$ 2 m) antenna with a (two-way half-power) beam width of approximately 6°. The online processing of these data was done with the statistical averaging technique designed to remove returns from birds (Merritt 1995). The RASS operated for 6 min at the beginning of each hour with 60-m resolution (no pulse coding) and the same minimum height of 150 m AGL.

Before profiler data can be used, it 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 when any of three quantities (signal-to-noise ratio, velocity, and spectral width) fall outside two or three standard deviations (depending on the quantity) 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. Data from hours with more than 12 outliers (out of approximately 20) were discarded. This technique will not remove contamination from persistent precipitation (Wuertz et al. 1988) and periods with precipitation are carefully avoided in the following comparisons.

2. Results and discussion

a. Profiler data availability

All days from 31 May through 6 October 1995 on which there were some data in each hour are analyzed here to show the height coverage of the profiler and RASS. There were 114 such days out of 129 possible. Figure 1 shows the height coverage of hourly wind data, broken down by time of day and by month. Data for an hour are counted as available if there are fewer than 12 outliers (approximately half the data points per hour); outliers are defined by the statistical cleaning method described above. No explicit attempt to remove data affected by rain was made before computing these statistics. Height coverage varies only slightly with time of day, data availability being slightly greater at middle heights (500–2000 m) in the daytime. Data are available more than half the time up to 2500 m. The 50% availability height is lowest in September and highest in August but always exceeds 2200 m. Martner et al. (1993) observed a 50% availability height of only approximately 1500 m for a similar system at Platteville, Colorado, in winter. Carter et al. (1995) show much higher coverage (50% availability to above 4 km) with similar systems at two tropical sites but using longer pulses.

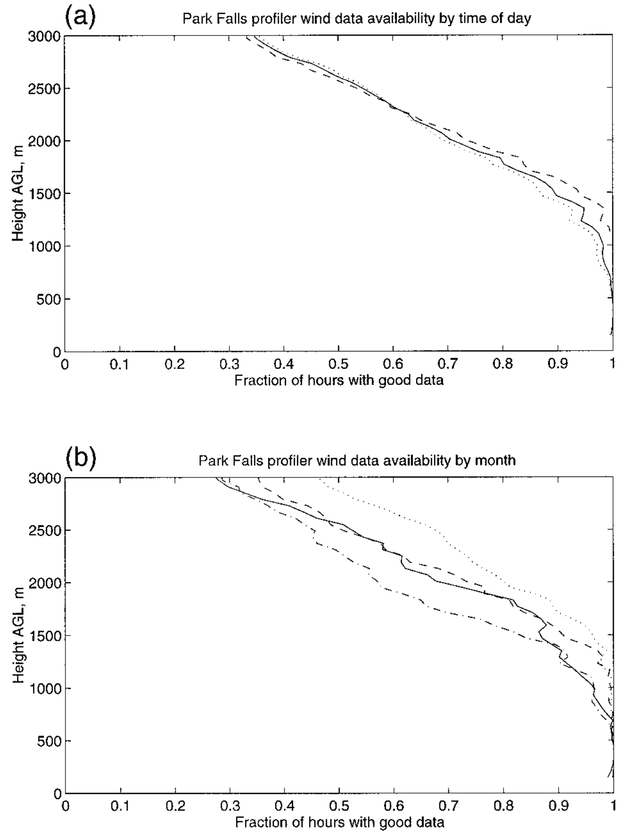


FIG. 1. Height coverage of profiler winds. (a) By time of day. Solid line is for all hours, dashed line for daytime (0800–1700 LST), and dotted line for night (1700–0800 LST). (b) By month. Solid line is for June, dashed line for July, dotted line for August, and dash–dot line for September.

The RASS height coverage is shown in Fig. 2. RASS coverage is better in daytime, probably because winds

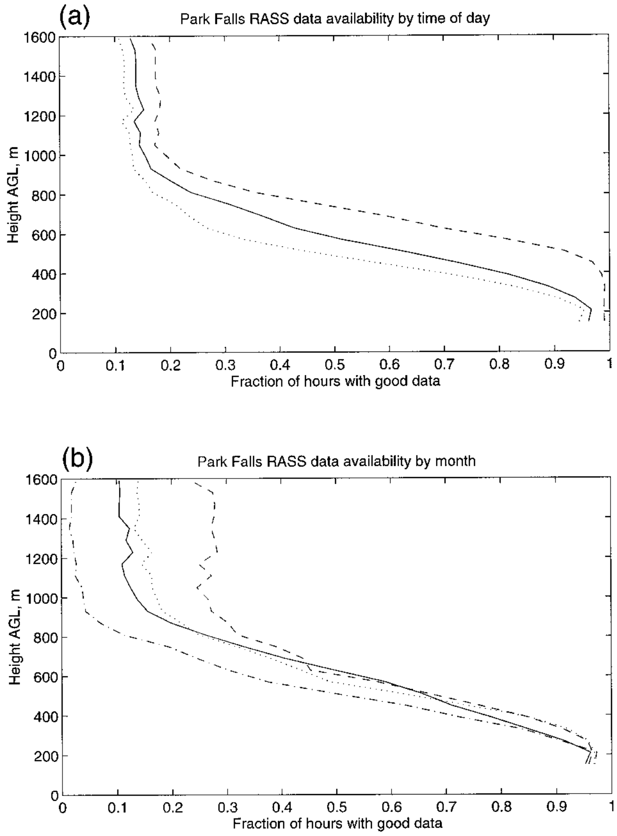


FIG. 2. Height coverage of RASS virtual temperature measurements. Line types are as in Fig. 1.

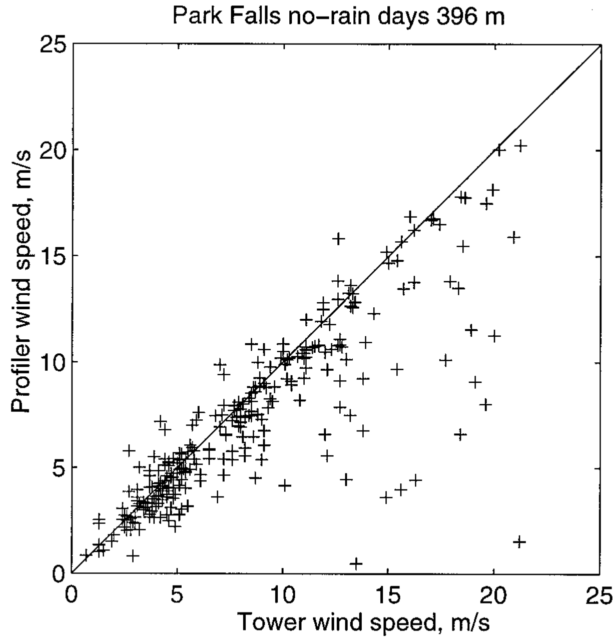


FIG. 3. Scatterplot of hourly average wind speed from the profiler vs the tower anemometer. The solid line is 1:1. Two hundred sixty-five points are included.

are lighter in the convective boundary layer or because turbulence broadens the scattered radiation pattern so that the effect of mean wind is mitigated. Data are available more than 50% of the time below 600 m overall, below 750 m in daytime, and only below 500 m at night. The variation with month is approximately 100 m. The coverage is comparable to that reported by Martner et al. (1993).

b. Wind speed and direction

For comparison with the tower instruments, data from 23 August through 28 September are used. This period had all instruments operating satisfactorily. A scatterplot comparing hourly average wind speed from the tower anemometer at 396 m and the corresponding profiler range gate for all days without rain (17) during this period are shown in Fig. 3. There are 265 points in the figure; hours failing the profiler quality criteria described above as well as instrument downtime account for the missing points. The agreement is generally quite good, although there are a number of points where the profiler wind speed is obviously too low. These are most likely due to ground clutter, which tends to bias the profiler speeds toward zero. Points with absolute differences greater than 3 m s^{-1} were removed before the statistics shown in Table 1 were calculated. Angevine and MacPherson (1995) found comparable although slightly smaller mean differences and standard deviations in a comparison between a nearly identical profiler and the Atmospheric Environment Service Canada Twin Otter. Martner et al. (1993) found much larger differences in a comparison between a different 915-MHz profiler and NWS rawinsondes, where the mean difference in the u component was 0.99 m s^{-1}, and the standard deviation of the differences in u and v were 3 m s^{-1}.

The wind direction scatterplot is shown in Fig. 4 for the same 265 h as in Fig. 3. Very few noticeable outliers are present. Points with differences greater than 40° and wind speeds less than 2 m s^{-1} were removed from the calculation of the statistics shown in Table 1. The mean difference is larger than reported by Angevine and MacPherson (1995) but not at all surprising considering the uncertainties inherent in determining the precise alignment direction of either tower instruments or profilers. The standard deviation of the difference is somewhat smaller than that reported by Angevine and MacPherson (1995).

There is no significant difference in wind speed or direction statistics between day and night, so convective turbulence neither improves nor degrades the comparison noticeably at this height (396 m). Including periods when rain may have been present makes little difference in the comparison because only a few hours of data are actually affected by rain.

TABLE 1. Statistics of comparisons between profiler/RASS and tower. Sign of mean difference is profiler/RASS − tower.

Comparison	Number of points	Correlation coefficient (r)	Mean difference	Std dev of difference
Wind speed (m s^{-1})	234	0.97	0.40	1.04
Wind direction (deg)	252	0.99	−4.98	8.97
T_v: RASS vs slow (K)	250	0.99	1.12	0.91
T_v: RASS vs sonic (K)	250	0.99	0.98	0.83
T_v: Fully corrected RASS vs slow (K)	250	0.99	0.74	0.92
Vertical velocity σ (m s^{-1})	167	0.64	0.048	0.29
Vertical velocity σ, resolved scale (m s^{-1})	167	0.68	0.060	0.25
Vertical velocity σ, unresolved scale (m s^{-1})	167	0.70	0.012	0.15

c. Virtual temperature

Virtual temperatures measured by RASS can be compared with two tower instruments: the slow thermometer/hygrometer and the sonic anemometer. Figure 5a shows the comparison with virtual temperature computed from measurements by the slow instrument for days when no rain was detected, and the statistics are shown in Table 1. These are 6-min averages at the beginning of each hour, and the same 250 points are included in Figs. 5a and 5b and Table 1. Differences greater than 5 K were removed. The similar comparison to the virtual temperature measured by the sonic anemometer is shown in Fig. 5b. The statistics (Table 1) are quite similar to those for the comparison with the slow sensor. There is a small bias between the sonic and the slow T_v measurements. Comparisons among three identical slow sensors at other tower levels suggest that the slow T_v measurement is accurate only to approximately ± 0.5 K.

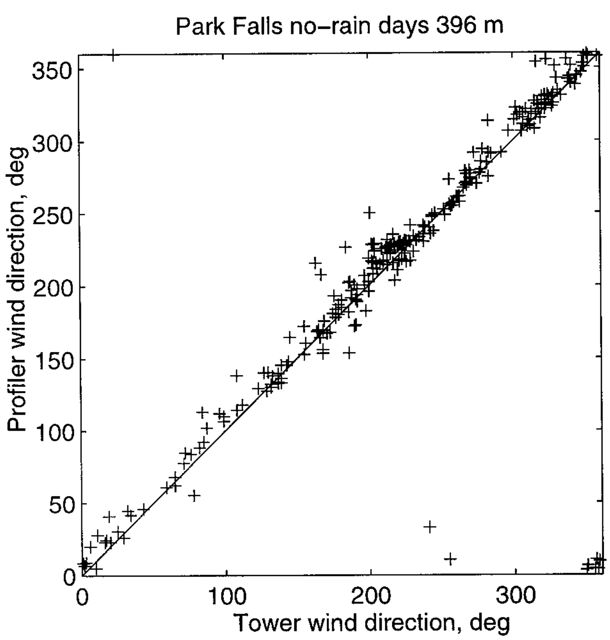
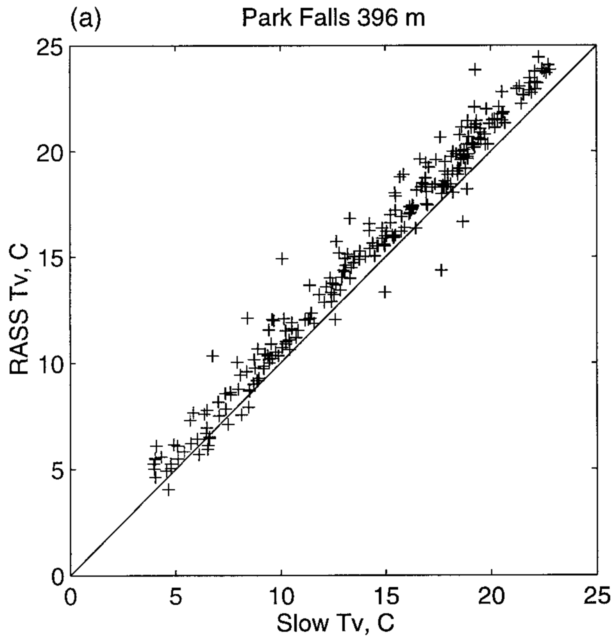


FIG. 4. Scatterplot of hourly average wind direction from the profiler vs the tower wind vane. The solid line is 1:1. The same 265 points are included as in Fig. 3.

All RASS data presented here use simultaneous vertical velocity correction (Angevine et al. 1994a; Moran and Strauch 1994). Some of the points above the 1:1 line may have been affected by incorrect vertical velocities due to hydrometeors. The vertical velocity measured by the profiler has a downward bias, even when rain is not present either in the gauge or in a subjective determination from the profiler data, as discussed for this dataset by Angevine (1997). This bias has a diurnal variation, being strongest in midday and weakest at night. The overall average vertical velocity bias is approximately -0.05 m s^{-1}, which would lead to a bias in the RASS measurement of less than 0.1 K. This is not a significant bias, but the effect probably contributes to the scatter in the comparison.

Both scatterplots show a slope significantly greater than 1, that is, the RASS T_v exceeds that measured by either tower sensor by a larger amount as the temperature itself rises. For the slow sensor (Fig. 5a) the slope is 1.04, and for the sonic anemometer (Fig. 5b) the slope is 1.05. These slopes are from an orthogonal distance regression assuming equal weights and variances for the two instruments. This study is able to establish a statistically significant slope because of the large number of points at a single height, which would be very difficult to achieve with radiosondes.

Several recent studies have attempted to understand the small height-dependent biases that are present in most comparisons of RASS with other sensors. Angevine and Ecklund (1994) described several effects that contributed to a positive bias (RASS reads high) in all but the lowest altitudes of a comparison between radiosondes and a RASS nearly identical to the one used in this study. These effects are a difference between the effective and assumed range of the measurement (''range error''), an error due to the displacement of the acoustic energy from the centerline of the radar beam [called wind and turbulence error by Angevine and Ecklund (1994), herein referred to as the ''displacement effect''] (Lataitis 1992), and approximations in the temperature retrieval equation. Peters and Angevine (1996)



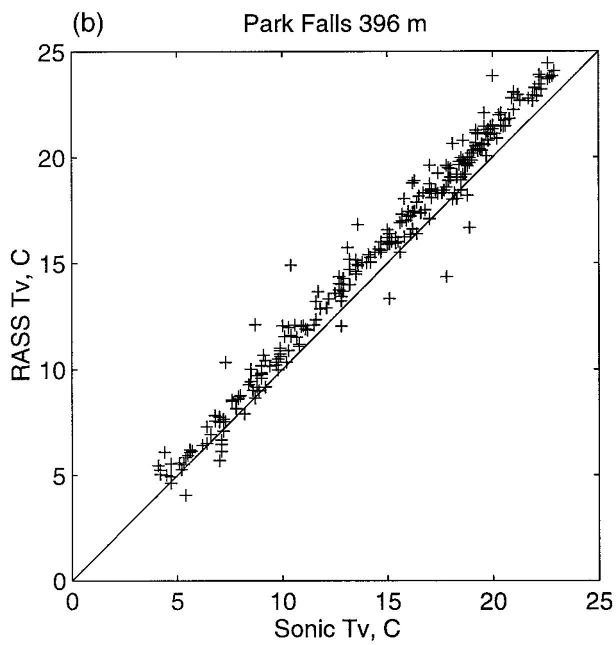


FIG. 5. Virtual temperature from RASS vs tower sensors. (a) Slow thermometer/hygrometer. (b) Sonic anemometer. The solid line is 1:1. The 250 points are 6-min averages at the beginning of each hour.

described another bias due to turbulence, which we will refer to as the "turbulence effect," and showed the effects of correcting this bias on comparisons with radiosonde flights at two different sites. Both the displacement and turbulence effects cause errors of the form $\Delta T/T$. Riddle et al. (1996) used the corrections suggested by the previous work in a large comparison between RASS and radiosondes at several sites in the tropical Pacific. In all these studies, biases on the order of a few tenths of a degree remained after all corrections had been applied. Of course, for many purposes, such biases are too small to be important. The height-dependent nature of the bias is more troubling since it makes gradient calculations difficult, but we do not address that problem further here.

The range error is proportional to the range resolution, which in this dataset is quite small (60 m). At most, the range error might contribute 0.05 K, so we ignore it. There is no correlation between the T_v difference and the vertical velocity variance measured by either the tower or the profiler, which indicates that the turbulence effect is not primarily responsible for the difference. Nonetheless, we correct for the turbulence and displacement effects.

Retrieval approximations can be a very significant source of error, up to 0.8 K at high temperature and humidity. The standard RASS retrieval formula is

$$T_v = \frac{c_a^2}{401.92} - 273.16, \tag{1}$$

where T_v is the virtual temperature (°C) and c_a is the acoustic velocity (corrected for vertical wind and the displacement and turbulence effects). Figure 6a shows the difference between T_v calculated by this formula and by the more precise formula of Cramer (1993). The corrections suggested by Angevine and Ecklund (1994) actually overcorrect the errors in (1) except at high temperature and humidity ($T > 25$°C and RH > 70%) because they mistakenly used Cramer's (1993) formula for the ratio of specific heats of a real gas in an ideal gas temperature formula. Unfortunately, Cramer's empirical formulas have 16 terms and cannot be solved for virtual temperature in closed form. We have explored a variety of solutions seeking a reasonably simple way to retrieve accurate temperatures from RASS. One approach is to use a simple power-law formula:

$$T_v = \frac{c_a^2}{401.87} - 273.37 + [4.43 \times 10^{-7}(c_a - 310)^{3.94}]\frac{\mathrm{RH}}{100}, \tag{2}$$

where RH is the relative humidity (%). The coefficients were derived by constructing a grid in T and RH. Each grid point then also has a value of T_v. The acoustic velocity c_a at each grid point was calculated by the formula of Cramer (1993), assuming a fixed CO_2 mole fraction of 314 ppm. Using the gridded data, T_v was fitted to c_a^2 at RH $= 0$ by least squares yielding the first two terms of (2), which are simply a corrected version of (1). The logarithm of the residual error in T_v at RH $= 72$% was then fitted to the logarithm of c_a, also by least squares, to yield the third (power law) term. The remaining error is shown in Fig. 6b, showing that (2)

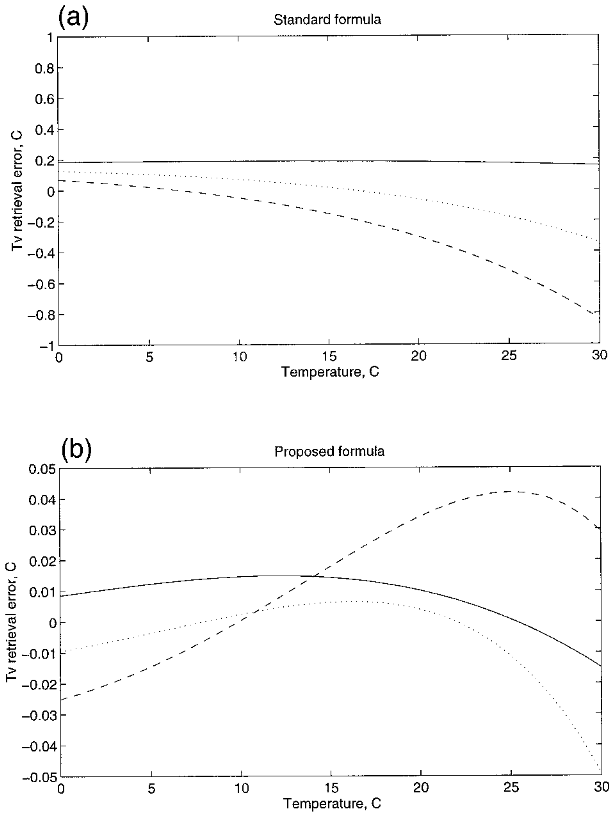


FIG. 6. (a) Error in retrieval of RASS virtual temperature using the standard formula (1) compared to the formula of Cramer (1993). The solid line is for 0% relative humidity, dotted line 50%, and dashed line 100%. (b) Error in retrieval of RASS virtual temperature using (2) compared to the formula of Cramer. Line types indicate relative humidity as in (a). Note that the vertical scale is reduced by a factor of 20 from (a).

produces estimates that are within 0.05 K of estimates from the full formula of Cramer (1993) for $0° < T < 30°$C and $0 <$ RH $< 100\%$. The particular coefficients of (2) are appropriate only for the specified temperature range. Different coefficients could be derived by a similar process for use at different temperature ranges, but the Cramer (1993) formula is only valid for this range. In general, RH measurements will not be available, but an approximation is sufficient. Such an approximation could be derived from, for example, the surface humidity.

Figure 7 shows the comparison of the fully corrected RASS to the slow tower sensor. The RASS data are corrected for the turbulence and displacement effects and the retrieval of (2) is used. The turbulence effect and displacement effect corrections reduce the mean RASS temperature by 0.29 and 0.14 K, respectively. The new retrieval (2) increases the mean RASS temperature by 0.05 K. The combined effect is to reduce the mean difference with respect to the slow tower sensor to 0.74 K. The corrections do not significantly change the correlation, the standard deviation of the difference, or the slope (Table 1).

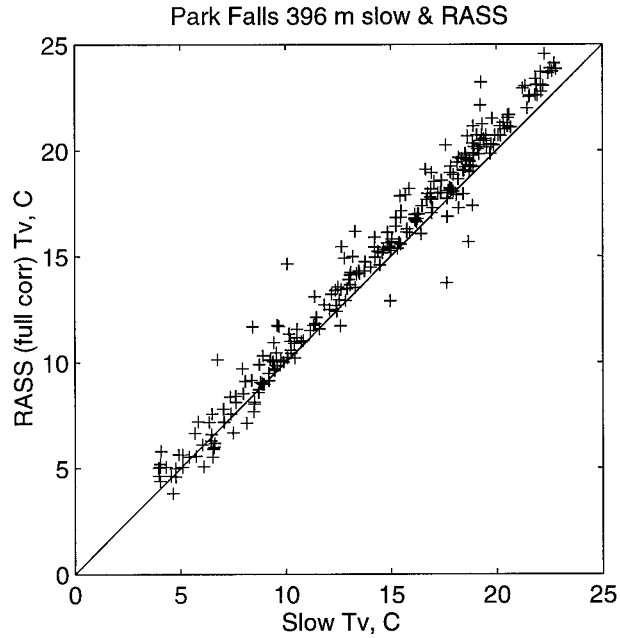


FIG. 7. Virtual temperature from RASS with turbulence, displacement, and retrieval corrections vs tower slow sensor. The solid line is 1:1. The same 250 points are included as in Fig. 5.

d. Vertical velocity variance

Having a sonic anemometer on the tower gives us an unusual opportunity to compare a direct measurement of turbulence from the profiler with an in situ sensor. In this case, we have chosen to compare the vertical velocity variance σ_w. To compute σ_w from the profiler data, we use the method of Angevine et al. (1994b). The total σ_w is the sum of the small- and large-scale variances. The small-scale variance is derived from the Doppler spectral width (second moment of the profiler Doppler spectrum) with a system bias of 1.25 m s^{-1} subtracted and includes timescales of 0–30 s. The system bias accounts for all effects that increase the spectral width, including signal processing, beam broadening, and other unexplained effects. The value of 1.25 m s^{-1} was determined empirically from examination of the profiles of spectral width and is slightly larger than the value of 1.11 m s^{-1} used by Angevine et al. (1994b) for a nearly identical profiler. The large-scale variance is simply the variance of the vertical velocity time series produced by the profiler and therefore includes timescales of 90 s to 1 h. For the sonic anemometer, the data for each hour are detrended and spikes are removed before the variance is computed. Figure 8 is a scatterplot of σ_w from the profiler and the sonic anemometer. Hourly values during the day (0800–1800 LST) from all days without rain are included in Fig. 8 and in the statistics shown in Table 1. Points failing the profiler data quality

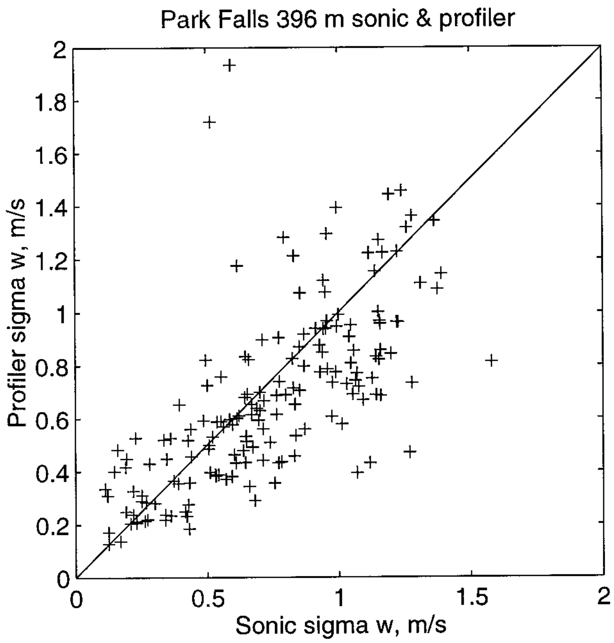


FIG. 8. Vertical velocity standard deviation on all scales from profiler vs sonic anemometer. See text for computation details. The solid line is 1:1. Hourly values for 167 h are included.

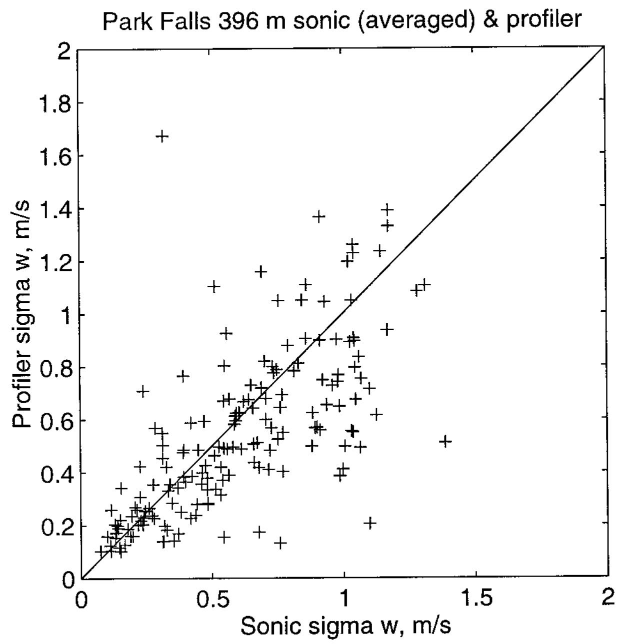


FIG. 9. Vertical velocity standard deviation on resolved scale only from profiler vs sonic anemometer. See text for computation details. The solid line is 1:1. Hourly values for 167 h are included.

criteria, those when the instruments were not operating and those with differences greater than 2 m s^{-1} were removed. There is very little bias. The correlation coefficient is moderate. In Fig. 9, we show a similar scatterplot for the large-scale variance, derived for the sonic anemometer by block-averaging the time series to 30 s and then computing the variance. This large-scale variance also shows little bias and a similar standard deviation and correlation coefficient (Table 1). Statistics for the small-scale variance alone are also shown in Table 1. The mean values are 0.60 m s^{-1} for the large-scale variance and 0.13 m s^{-1} for the small-scale variance, both from the sonic anemometer. The statistics indicate that both small and large scales are contributing to the variance, although the small scale contributes only about one-fifth of the total; that the measurements of both scales contain real signal; and that the choice of system bias is very close to correct. Nighttime hours are excluded from both comparisons because the profiler variance on both scales is often unreasonably large at night, probably due to weak signal and increased contamination. The correlations are reduced to about 0.5 on both scales if nighttime data are included.

White (1995) found a similar correlation in the structure function parameter for horizontal wind fluctuations C_u^2 in a comparison between a boundary layer profiler and a sonic anemometer at 250 m AGL on the Boulder Atmospheric Observatory tower. It is not possible from either this study or that of White (1995) to partition the scatter between instrumental and atmospheric effects.

3. Conclusions

We have shown comparisons of wind speed and direction, vertical velocity variance, and virtual temperature between a boundary layer wind profiler/RASS and instruments at 396 m AGL on a tower. The tower and the profiler/RASS were separated by 8 km in rolling, forested terrain. The comparisons generally support the accuracy and precision reported for profilers and RASS in previous studies. We have also discussed the height coverage of the profiler/RASS under these conditions (late spring–early autumn midlatitude continental mixed forest).

The profiler wind speed was biased low, probably by ground clutter. The standard deviation of the wind speed difference was approximately 1 m s^{-1}, as in other studies. This includes atmospheric effects and the uncertainty of both instruments, so the profiler wind speed uncertainty is less than 1 m s^{-1}. The wind direction also had a small bias, but the standard deviation of the difference was quite small, less than 9°.

Virtual temperature comparisons showed that the precision of the RASS measurement is better than 0.9 K. A bias was also present, but we are unable to attribute it to one instrument or the other. We proposed and used a new temperature retrieval method, applicable to the particular temperature range relevant to this study, which could be used as a pattern to derive similar retrievals for other conditions. This method produces smaller errors than the usual method when compared to theory. Corrections for turbulence and displacement effects reduced the bias, but the retrieval method increased it slightly. The observed slope, slightly greater than unity in the virtual temperature comparisons, may be due to the turbulence and displacement effects, which produce errors that are proportional to temperature. The slope, however, does not disappear when corrections are made for these effects.

The opportunity to compare turbulence measurements from remote sensors (such as the profiler) and in situ instruments (such as a sonic anemometer) is somewhat unusual. The results of this comparison indicate that the techniques for computing vertical velocity variance from the profiler produce reliable results. It is particularly interesting that the comparison is good at both small and large (unresolved and resolved) scales. A more sophisticated calculation could probably be made by using a wind speed–dependent system bias.

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