The Accuracy of RASS Temperature Measurements Corrected for Vertical Air Motion

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ABSTRACT

Temperature measurements made with a 50-MHz wind profiler equipped with a radio acoustic sounding system (RASS) are compared with radiosonde observations (raobs) during a 5-week period in the fall of 1991. The accuracy of the RASS temperature measurements corrected for vertical air motion is reported. Measurements made during a period when vertical air motion was observed showed a mean improvement of 0.7°C after correction. The rms differences between the RASS observations and the raobs showed improvement at all the measurement heights when the correction for vertical air motion was made. The accuracy for all the observations is reported to be 0.9°C. The remaining differences in the temperature are compared with a model of RASS errors induced by horizontal winds and turbulence.

1. Introduction

Accurate measurements of temperature are of importance in weather prediction and the study of the dynamics of the atmosphere at all scales. Historically, balloon-borne instrument packages have been used to measure the vertical profiles of many atmospheric parameters. The repeatable accuracies of the temperature measurements from these radiosonde observations (raobs) have been shown to be 0.6°–0.8°C (Hoehne 1980), and more recently 0.3°–0.4°C (Ahnert 1991). New remote sensing techniques that hope to improve on the spatial and temporal characteristics of the balloon systems must achieve comparable measurement accuracies.

The radio acoustic sounding system (RASS) is a ground-based remote sensing technique that provides routine vertical profiles of virtual temperature from a height several hundred meters above the surface through the lower 5–7 km of the troposphere. RASS has been applied to wind-profiling radars at frequencies of 50, 404, and 915 MHz at the Environmental Technology Laboratory (ETL, formerly the Wave Propagation Laboratory) of the National Oceanic and Atmospheric Administration (NOAA) with excellent results (May et al. 1988a). Vertical profiles of virtual temperature can be measured with the same temporal and spatial resolution the radar uses to measure winds. RASS has also been applied to 404-MHz radars in the NOAA Wind Profiler Demonstration Network, and temperature profiles with height coverage starting at 500 m and extending to above 3 km AGL have been made during routine observations (Moran et al. 1991).

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The technique combines sensitive clear-air Doppler radars that measure a vertical profile of vertical and horizontal atmospheric winds, with an array of vertically pointing acoustic sources. The acoustic sources produce sound waves that perturb the refractive index. The perturbations propagate vertically at the local speed of sound and serve as a target for the radar. When the acoustic wavelength is Bragg matched to half the radar's wavelength, the radar receives a strong echo from this artificially generated reflectivity grating, and the resulting Doppler shift is a measure of the local speed of sound in the radar volume. The local sound speed C_a is related to the virtual temperature by

$$T_v = \left(\frac{C_a}{20.047}\right)^2,$$

so a vertical profile of sound speed can be converted to a profile of virtual temperature. (In contrast, wind profiles are typically retrieved by measuring Doppler shifts associated with the scatter of radio waves from clear-air turbulence, which is advected through the radar volume by the background wind.)

The speed of sound measured by the radar is affected by local air motion, and the velocity of the air must be subtracted from C_a to obtain an accurate temperature measurement. A vertical wind of 0.3 m s^{-1} will result in a temperature error of about 0.5°C unless the air motion is measured and subtracted from the RASS data. The radar routinely measures the velocity of the vertical wind, and so a correction can be made to improve the accuracy of the temperature profiles.

Early work with RASS either ignored the effects of vertical air motion or used time averaging to reduce the effects (May et al. 1988a). This achieved reasonably good results as long as the mean vertical wind component was small during the averaging time. However, under many conditions such as convection, frontal passages, and gravity waves, the variability of vertical air motion over the dwell time of a RASS observation (typically 4–6 min) can result in a large mean error in the measured temperature (Weber et al. 1992). These errors can be reduced by observing the wind in time intervals adjacent to the RASS measurements and estimating a correction for the vertical motion. But, with temporal fluctuations in the wind field of the same scale as the RASS observation time, simultaneous measurements of wind and temperature are needed to provide the smallest error in the corrected estimate.

Until recently, it was not easy to make simultaneous measurements of the velocity of the vertical wind and the speed of the acoustic waves. Real-time spectral processors were needed that could analyze the large Doppler shifts associated with the acoustic signal (330 m s^{-1}) while maintaining the high resolution (0.3 m s^{-1}) needed for accurate measurements of wind and temperature. A new radar processor developed by NOAA's Aeronomy Laboratory provides simultaneous measurement of both the vertical wind velocity and the acoustic sound speed with the precision needed to correct for air motion (Angevine et al. 1994).

During the months of October and November 1991, a study was conducted comparing RASS temperature measurements from the 50-MHz wind profiler at Platteville, Colorado, and radiosonde observation (raob) temperatures from the Denver, Colorado, National Weather Service Forecast Office at Stapleton International Airport. This study reports on the accuracy of the temperature profiles from the RASS soundings corrected for vertical wind.

2. Observations

Research done at ETL in recent years has shown that the accuracy of RASS-measured virtual temperature profiles, when compared with raob measurements, is about 1°C when no correction is made for vertical winds (May et al. 1988b). To measure the temperature to an accuracy of 0.5°C, the radar must measure both the vertical wind and the speed of the acoustic signal with an accuracy of about 0.2 m s^{-1}. May et al. (1988a), showed that under nearly ideal conditions the uncertainties in the RASS temperature measurements approach the theoretical limit of radar velocity measurements from a deterministic acoustic signal. The predicted uncertainty varies with altitude (signal-to-noise ratio), and for the 50-MHz radar, the uncertainty for heights up to 10 km was shown to be less than 0.2°C. In contrast, the theoretical uncertainties with which the radar can measure the Doppler shift in the wind, which is the measurement of backscatter from a random process, are larger because of the statistical differences between the two scattering mechanisms. It is expected (May et al. 1988b) that the factor limiting the accuracy of the temperature, when correcting for vertical motion, will be the uncertainties in the measurement of the vertical wind speed. Antenna beamwidth has been shown to be a significant influence on the accuracy of vertical wind measurements in the presence of strong horizontal flow. Other factors, such as ground clutter, can contribute biases in the estimate of the vertical velocities.

The ability of short-wavelength radars (UHF) to measure vertical winds is limited to nonprecipitating conditions. The strong reflectivity associated with precipitation masks the weaker atmospheric echo and precludes the use of the vertical velocity estimate to correct the temperature profiles. The vertical velocity measured by the 50-MHz radar used in this study is not influenced by light precipitation or snowfall.

The radar measurement of the speed of the acoustic signal is also subject to errors caused by other factors. The placement of the acoustic source with respect to the radar antenna, and horizontal winds were both shown to bias the estimate of the speed of sound (Peters and Kirtzel 1994). It has also been suggested that turbulence can contribute an offset to the measured sound speed (Lataitis 1992). It has been generally assumed that the cumulative effect of these factors on the accuracy of the temperature measurement is smaller than the errors due to the presence of low-to-moderate vertical velocities. Temperature profiles corrected for vertical air motion should show improved accuracies, and the remaining uncertainties, especially at higher altitudes, may be attributed to errors associated with horizontal winds and turbulence. Reducing the uncertainties in the estimate of the temperature due to vertical air motion will enable further studies to examine other sources of error in greater detail.

A recent study that used a radar processor identical to the one used in this study compared the velocities of the clear air with the simultaneous RASS velocities and found that the short-term fluctuations in the RASS velocity estimates were highly correlated with fluctuations in the vertical wind (Angevine et al. 1994). The mean vertical winds observed were often nonzero during the RASS dwell time, resulting in corrections to the measured temperatures of the order of 0.5°C.

In this study we compare RASS virtual temperatures from the Platteville 50-MHz wind profiler with raob temperatures obtained from Denver, both before and after the correction for vertical motion was made. The effect of the 40-km separation between the sites was reduced by choosing times when meteorological conditions were similar. The observations extended from 10 October through 15 November 1991, with two daily raob launches at 1100 and 2300 UTC. Seventy-two individual soundings were available during this period and 58 were used in this study. The soundings that were not used contained instrumental errors or observational discrepancies attributed to the 40-km separation. The wind profiler at Platteville was used for this comparison because it can make accurate measurements of the vertical wind without the influence of ground clutter. The first height observed by the radar was 2.2 km AGL, high enough to reduce the effects of the local boundary layer at this time of year.

The measurements are divided into three periods, based on differing conditions. The first period, 10 October–15 November, consists of all the comparisons during the 5 weeks of observations. The second period, 10–27 October, consists of only the observations with moderate (>0.3 m s^{-1}) vertical velocities. The Platteville site is 60 km east of the Front Range of the Rocky Mountains, and moderate winds at mountaintop height can produce vertical winds associated with wave activity. The third period, 10–15 October, consists of measurements during several weak frontal passages and a period of moderate upper-level winds.

The RASS virtual temperatures were taken from an average of four to six individual profiles sampled during a 6-min period once every half hour. The uncorrected and corrected temperatures passed independent consensus tests (a measure of consistency) (May and Strauch 1989) before they were compared with the closest raob sounding. The raob data were processed to give a height-averaged virtual temperature, similar to the RASS volume-averaged virtual temperatures. Figures 1 and 2 show the results of the three comparisons.

The first set of figures is a series of scatterplots that compare the RASS virtual temperatures with raob measurements both before and after the correction for vertical wind was made. The scatterplots for the uncorrected RASS temperatures (Figs. 1a–c) show a larger spread about the diagonal (zero error line) than do the corrected plots (Figs. 1d–f). This indicates that the correction for vertical air motion has reduced the uncertainty in the measured temperatures for all three periods. Of note are Figs. 1b and 1e, which are for the cases with moderate vertical motion (>0.3 m s^{-1}), period 2. The rms differences for the uncorrected temperatures were 1.7°C for these observations; rms differences for the corrected temperatures were 1.0°C showing an improvement in the estimate by 0.7°C. Improvements during the other periods were 0.3°C and 0.8°C for the first and third periods, respectively.

The second set of graphs illustrates the rms difference in the virtual temperature between the raob and RASS observation at each height for the same three periods (Figs. 2a–c). The corrected RASS temperatures showed improvements at heights below 5.5 km. This is consistent with the heights at which moderate vertical motion (>0.3 m s^{-1}) was observed. During each of the periods, several of the soundings occurred during times when the observed vertical velocities were associated with mountain wave activity. This activity also contributed to the errors caused by vertical air motion. The overall accuracy for the third period when the conditions were the most favorable was 0.7°C, whereas periods 1 and 2 had accuracies of 0.9°C and 1.0°C, respectively.

3. Discussion and significance

The measurements used in this study were divided into three periods to identify the significant features of the observations. For the first period, where 58 soundings were used over the 5 weeks of observations, the significance is in the general trend of the improvements. The improvements during this time were the smallest (0.3°C), suggesting that the vertical correction improved the temperature estimates in only a small fraction of the total cases, those with moderate vertical air motion. The accuracy of all the uncorrected measurements from this period is consistent with the result from earlier studies, and the corrected measurements improved on the estimates of the temperature by only 0.3°C.

The second period identified observations made at times when moderate vertical winds (>0.3 m s^{-1}) were present. The improvement in the accuracies for this period was 0.7°C, and this confirmed that a large source of the rms differences was vertical air motion. The magnitude of the improvement was consistent in height (Fig. 2b).

The third period of observations produced the best raob–RASS comparisons, having an overall accuracy of 0.7°C and an improvement of 0.8°C when the measurements were corrected for vertical motion. Moderate upper-level winds and several weak frontal passages contributed to the variety of conditions. During this period, conditions were the most favorable for comparing the separated stations, and only one sounding was removed because of any differences in atmospheric conditions.

The standard deviation (STD) of the difference in the corrected virtual temperatures is shown in Fig. 2a and gives an estimate of the uncertainties (random errors) in the observations. There are two errors associated with the horizontal separation of the sampling volumes that can contribute to the uncertainty in the comparisons. The first is due to normal atmospheric variability of temperature between two stations. A study by Barnes and Lilly (1975) reported that two simultaneous soundings with a horizontal separation of 40 km (the distance between Denver and Platteville) had temperature differences of the order of 0.5°–1.1°C. The second source of error is related to perturbations in the temperature field due to wave activity in the atmosphere. As previously mentioned, the RASS site is in the lee of the Rocky Mountains and strong horizontal winds at mountaintop levels often produce vertical winds that are associated with waves. Modest vertical winds, of the order 0.2 m s^{-1}, can cause a disturbance in the temperature profile of 0.5°C. Since the observed vertical wind velocities were often larger than this, the disturbance in the vertical profile of temper-

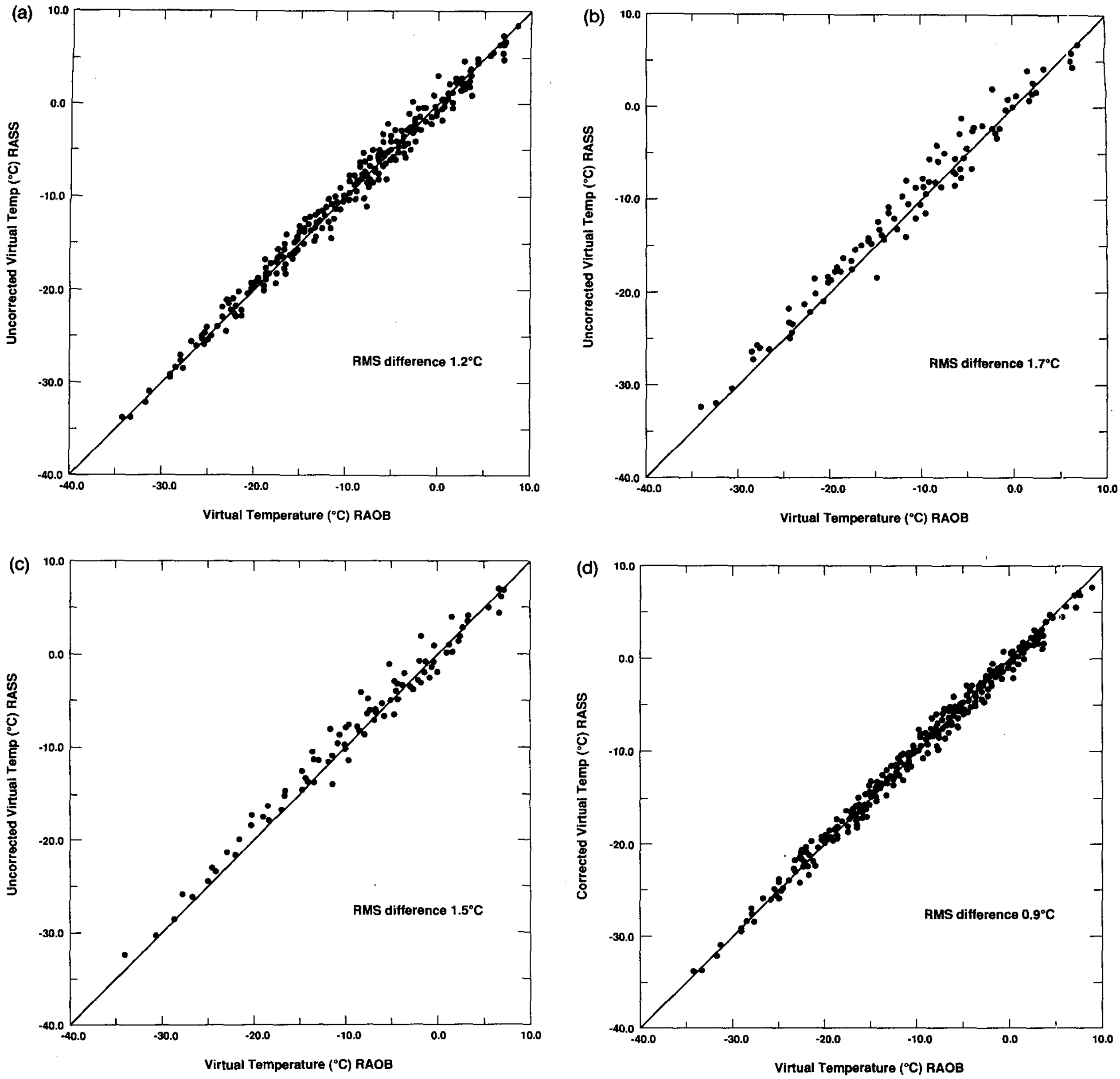

FIG. 1. Scatterplots of virtual temperature that compare RASS measurements from Platteville with raobs measurements from Denver. (a) 10 October–15 November 1991, uncorrected RASS; (b) 10–27 October 1991, uncorrected RASS; (c) 10–15 October 1991, uncorrected RASS; (d) 10 October–15 November, corrected RASS; (e) 10–27 October, corrected RASS; (f) 10–15 October, corrected RASS. The data for 10 October–15 November consist of all comparisons; 10–27 October consists of only observations with moderate vertical winds; 10–15 October includes several weak frontal passages and moderate upper-level winds. RASS-measured temperatures that were not corrected for vertical air motion (a)–(c) show more spread than do corrected temperatures (d)–(f).

ature could be of the order of 0.5°–1°C. The effects of these two errors were reduced by editing the observations to remove soundings where atmospheric conditions caused large differences in the temperature. The editing, however, did not remove all the small differences associated with these errors and we would expect uncertainties of the order of what is being observed.

The characteristics of the uncertainties in the measurements of the velocity of the acoustic signal and the vertical wind velocity are summarized in Fig. 3 for the second period. The magnitude of the mean vertical wind profile is also shown; it peaks at an altitude consistent with motions induced by mountain wave activity and falls off sharply at heights above and below this region. The uncertainties in the wind and RASS measurements are of the same magnitude up to 5 km. At altitudes above this the uncertainties in the RASS measurements are unchanged while the uncertainties

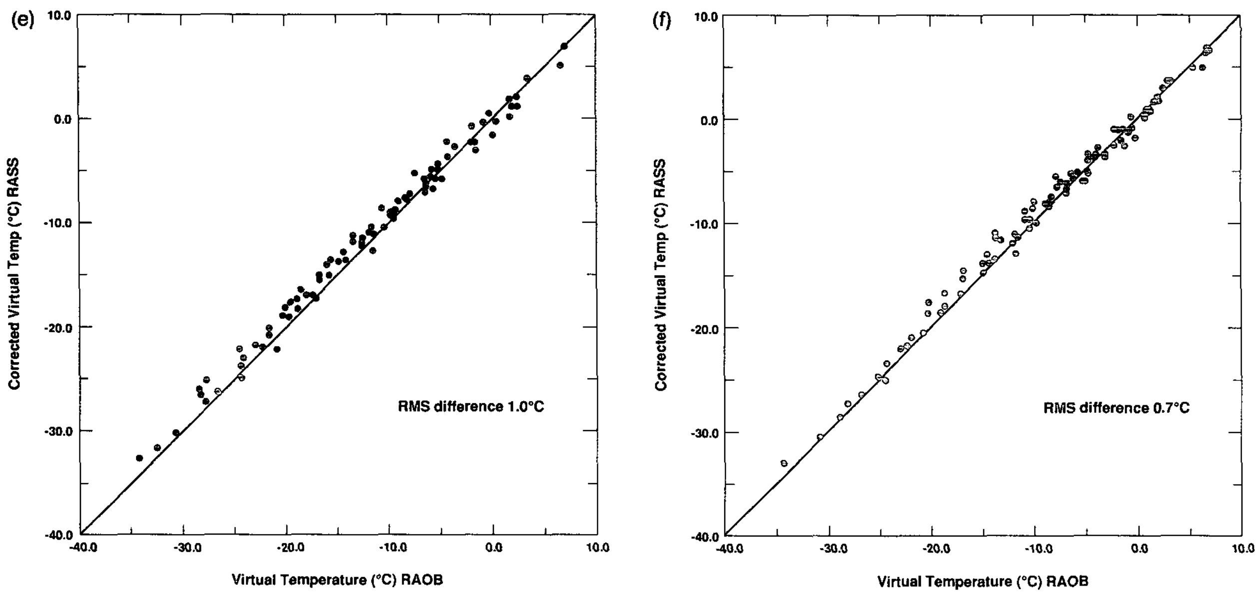

FIG. 1. (*Continued*)

in the wind measurements decrease. This suggests that at higher altitudes other factors such as strong horizontal winds may have an influence on the measurement errors.

One factor that may limit the accuracy of the temperature measurements in the lower altitudes is the ability of the radar to make accurate vertical velocity estimates under light wind conditions. The uncertainty of the vertical wind estimate may play a significant role in increasing the uncertainty of the corrected RASS temperatures and it may be better to use the correction under these conditions only when the magnitude of

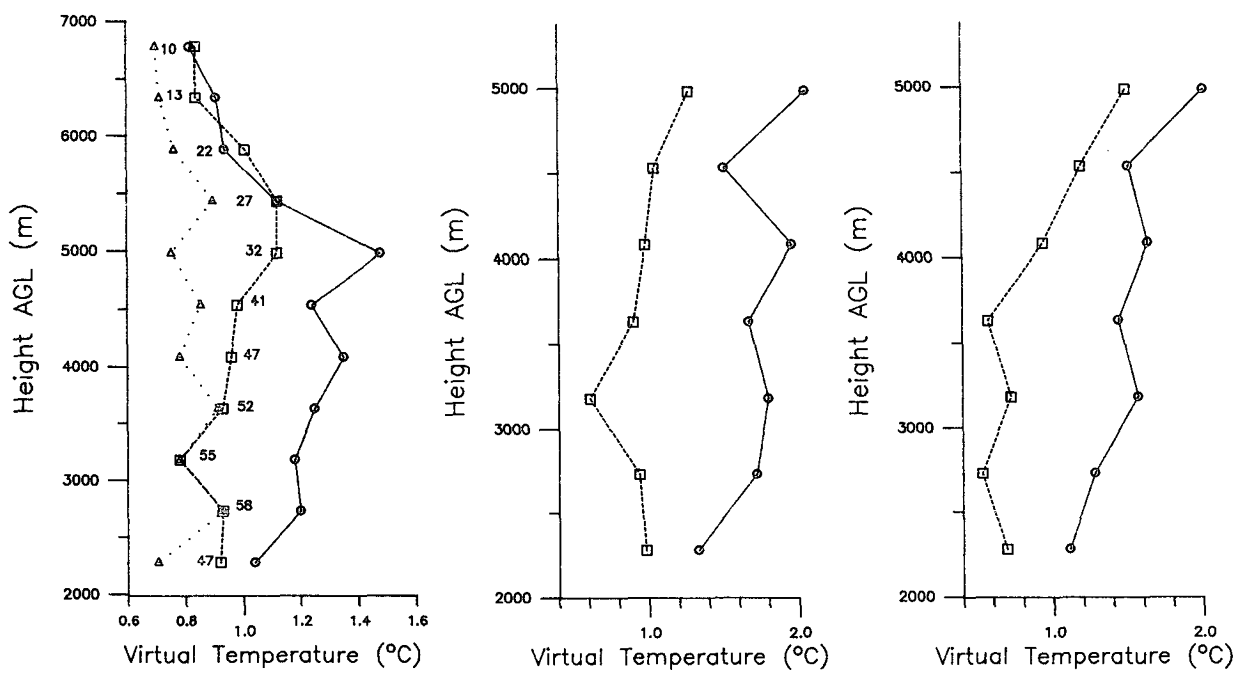

FIG. 2. Root-mean-square differences between the raob and RASS virtual temperature measurements both before (solid curves, circles) and after (dashed curves, squares) the correction for vertical air motion was made. (a) 10 October–15 November 1991; (b) 10–27 October 1991; (c) 10–15 October 1991. The total number of soundings used at each height is identified in (a), as is the STD of the virtual temperature difference (dot, triangles).

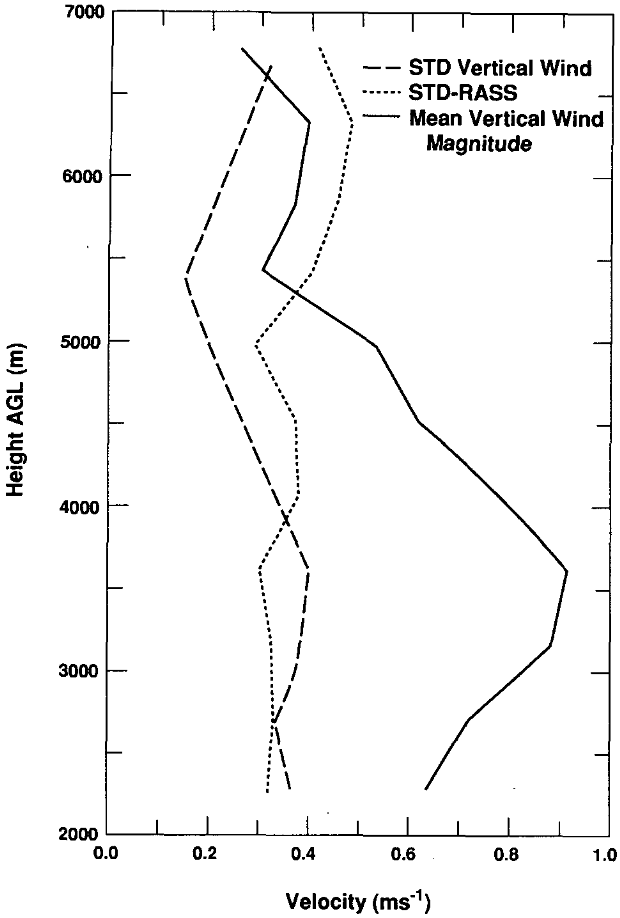

FIG. 3. The standard deviations in the velocity of the acoustic signal (RASS) and wind velocity measurements made during the period when modest levels of vertical wind velocity were observed. Also shown is the mean vertical wind.

the measured vertical wind exceeds the expected error in the measurement.

We examined 400 individual time–height samples under light wind conditions to see if the statistics of the corrected temperatures were significantly different than the uncorrected temperatures. We found that in over half of the cases there was no noticeable difference in the standard deviation of the corrected and the uncorrected estimates. In the remaining cases the difference was less than 0.2°C. For these data, it was found that the statistics of the corrected temperature were dominated by uncertainties in the uncorrected RASS measurements rather than the uncertainties in the wind estimates. This may be an artifact of RASS temperature measurements made using a 50-MHz wind profiler. At this operating frequency, specular reflections are often observed on the vertical beam. This improves the signal-to-noise ratio and reduces the uncertainty of the vertical wind estimates. Specular return has not been observed on radars that operates at 404 and 915 MHz and the uncertainties in the vertical wind estimates, under light wind conditions, may have more of an effect on the corrected temperatures.

The corrected profile of mean temperature difference for the entire set of observations is shown in Fig. 4. The profile shows a trend in the mean difference that suggests the effect of a systematic bias in the measurements. RASS temperatures are cooler than the raob temperatures at lower heights and warmer than the raob temperatures at upper heights. Recent work by Lataitis (1992) has suggested a model for the temperature error for RASS that is dependent on the magnitude of the horizontal winds, the acoustic source placement relative to the radar, and the presence of moderate turbulence in the lowest several kilometers. For conditions with little or no turbulence, the horizontal wind causes a displacement in the virtual acoustic source, and the radar beam Bragg matches with the tilted acoustic wave at a slightly different frequency, causing a measurement error. For conditions with moderate turbulence, perturbations in the acoustic wave fronts due to turbulence are advected by the wind and tracked by the radar causing a slight (Doppler)

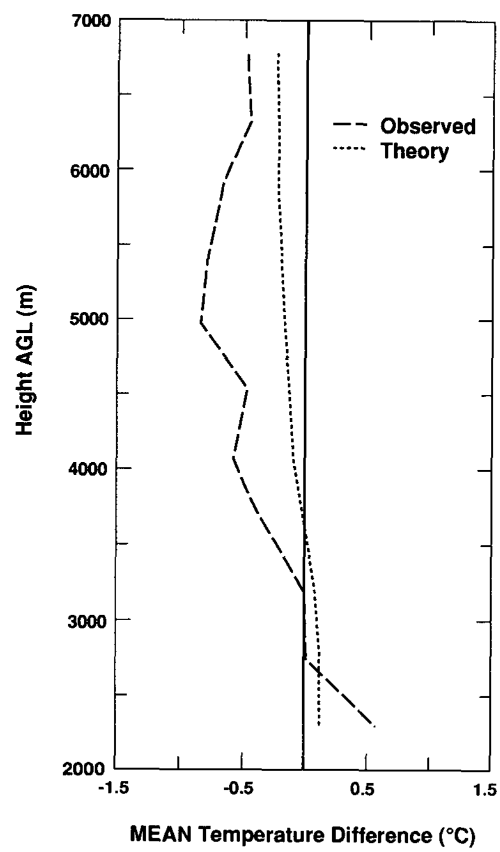

FIG. 4. The mean temperature difference between raob measurements and RASS measurements corrected for vertical air motion. The dotted curve is an estimate of the errors expected from turbulence and horizontal wind; the dashed curve is from observations. RASS temperatures appear cooler at lower heights and warmer at upper heights due to the effects of horizontal winds and turbulence.

shift in the measured velocity. The errors that the model predicts (dotted curve) are a combination of these two effects and follow the same general shape of the errors observed by the RASS (dashed line). Using a surface wind of 6 m s^{-1} and a gradient of 1 m s^{-1} km^{-1}, with an acoustic source centered on the radar antenna, the theoretical curve shown in the figure underestimates the errors by nearly 0.5°C. Larger wind gradients would produce theoretical results that are closer to the observed errors. Also, refinements in the model used would yield more consistent results. Additional observations are clearly needed to unambiguously identify remaining biases in the corrected RASS temperatures.

In all the periods identified, the correction for vertical air motion showed an improvement in the virtual temperature measured by RASS. The accuracy of all the observations was 0.9°C, which was of the order of the largest improvement in the measurements when the correction was made. The measured accuracy of 0.9°C does not approach the expected accuracy of 0.2°C suggested in earlier work. However, that work did not include estimates of errors from horizontal winds and turbulence, which are believed to contribute uncertainties of the order of what now has been observed.

The volumes sampled by the two techniques are separated by 40 km and this contributed uncertainties that were not associated with measurement errors. In this regard these comparisons are significant with respect to the size of the improvement that can be expected when vertical winds contribute to uncertainties in the corrected temperatures. This suggests that comparisons that sample the same volume may show further improvements.

4. Summary

The ability to measure the vertical air motion and the temperature simultaneously extends the capabilities of a 50-MHz wind profiler equipped with RASS to a broader set of meteorological conditions. RASS temperature profiles that have the uncertainties due to vertical wind removed allow the study of other (smaller) sources of errors caused by horizontal winds and turbulence.

RASS has become an important technique in the development of next-generation upper-air observing systems. The NOAA Wind Profiler Demonstration Network will add RASS capability to five profilers. They will have range resolution of 250 m and measure temperature profiles to 3–5 km. Combining RASS profiles with satellite radiometry will improve retrieved temperature sounding through the troposphere and into the stratosphere (Schroeder et al. 1991). The accuracy of the measurements corrected for vertical air motion is limited by the radar's ability to measure the vertical wind and by the effects of horizontal wind and turbulence. Precipitation echoes are often several orders of magnitude stronger than clear-air signals with the 404-MHz profilers in the demonstration network and prevent the measurement of the vertical air motion, so the correction of RASS temperatures is limited to nonprecipitating conditions. The significance of comparing RASS and raobs may be limited by the accuracy of the raobs (0.4°C), and a comparison between multiple wind profilers equipped with RASS at different frequencies may provide the best technique to verify accuracy.

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