UCRL-TR-234138

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IMPROVED WIND AND TURBULENCE MEASUREMENTS USING A LOW-COST 3-D SONIC ANEMOMETER AT A LOW-WIND SITE

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August 30, 2007

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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For submission to *Journal of Atmospheric and Oceanic Technology*

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ABSTRACT

A year of data from sonic anemometer and mechanical wind sensors was analyzed and compared at a low-wind site. Results indicate that 15-minute average and peak 1-second wind speeds (u) from the sonic agree well with data derived from a co-located cup anemometer over a wide range of speeds. Wind direction data derived from the sonic also agree closely with those from a wind vane except for very low wind speeds. Values of standard deviation of longitudinal wind speed (σ_u) and wind direction fluctuations (σ_θ) from the sonic and mechanical sensors agree well for times with $u > 2$ ms^{-1} but show significant differences with lower u values. The most significant differences are associated with the standard deviation of vertical wind fluctuations (σ_w): the co-located vertical propeller anemometer yields values increasingly less than those measured by the sonic anemometer as u decreases from 2.5 approaching 0 ms^{-1}. The combination of u over-estimation and under-estimation of σ_w from the mechanical sensors at low wind speeds causes considerable under-estimation of the standard deviation of vertical wind angle fluctuations (σ_ϕ), an indicator of vertical dispersion. Calculations of σ_ϕ from sonic anemometer measurements are typically 5° to 10° higher when the mechanical instruments indicate that $\sigma_\phi < 5°$ or so. The errors in both the propeller anemometer and cup anemometer, caused by their inability to respond to higher frequency (smaller scale) turbulent fluctuations, can therefore lead to large (factors of 2 to 10 or more) errors in the vertical dispersion during stable conditions with light winds.

1. Introduction

Sonic anemometers measure wind velocity by measuring the effect of the wind on the transit times of ultrasonic acoustic pulses. A sonic temperature can also be derived from the speed of sound. The sonic anemometer is widely recognized as one of the best instruments for measuring and studying atmospheric turbulence. Desirable characteristics of the sonic anemometer include lack of moving parts, linear dynamic response, good directional response, and frequency response limited only by the sound path length. The first sonic anemometers were large and expensive (Coppin and Taylor 1983), limited to one axis (used primarily to measure vertical turbulence), and developed because there was inadequate instrumentation to measure atmospheric turbulence to support research (Wieser et al. 2001). Further breakthroughs allowed development of improved and more reliable vertical and three-dimensional (3-D) sonic anemometers used primarily for research.

Inexpensive two-dimensional (2-D) sonic anemometers are becoming more widely used for routine wind monitoring because of their low or no maintenance requirements. Sonic anemometers are also capable of measuring wind and turbulence statistics at very low wind speeds, below starting thresholds of mechanical wind sensors. For example, the National Weather Service and Federal Aviation Administration are replacing the cup anemometers and wind vanes that are currently used in the Automated Surface Observing System (ASOS) with 2-D sonic anemometers (Lewis and Dover 2004). The Tennessee Valley Authority has also selected an ultrasonic anemometer to replace the traditional wind vane and anemometer (Wastrack et al. 2001). Until recently, only expensive research sonic anemometers were available for estimating vertical turbulent wind variables in order to estimate vertical dispersion and heat, evaporative and momentum fluxes. Routine wind and turbulence monitoring by 3-D sonic anemometers is becoming more common as well (e.g., see Baxter et al. 2003 and Vidal and Yee 2003).

This paper describes the results of comparing horizontal winds and 3-D turbulent statistics measured by mechanical wind sensors with a co-located 3-D sonic anemometer over an entire year. Implications of the measurement differences and the feasibility of using the 3-D sonic anemometer for routine monitoring are discussed.

2. Study Description

The Terrestrial and Atmospheric Monitoring and Modeling (TAMM) Group of the Environmental Protection Department (EPD) at the Lawrence Livermore National Laboratory (LLNL) is responsible for meteorological monitoring and analysis to support emergency and regulatory dispersion modeling, Laboratory field activities and operations, and special studies. The TAMM Group acquired and installed an inexpensive 3-D sonic anemometer at the 10-m level on one of its meteorological towers to supplement its monitoring program. Goals include acquiring data to make accurate estimates of evaporation (evaporative heat flux), vertical heat and momentum flux, and improved vertical turbulent fluctuation data. This instrument also serves as a redundant sensor to co-located mechanical sensors at the same height.

This study was made at a 35-m meteorological tower located on the northwest corner of LLNL's Livermore site (see Figure 1). The site is located on the eastern side of the Livermore Valley, about 50 km east of Oakland and at an elevation of 174 m. The site is flat and the terrain slopes up gently toward the southeast at a grade of slightly more than 1%. Annual grasses grow at the site. The closest obstructions include a north-south line of eucalyptus trees about 125 m to the east, commercial buildings 220 m to the north and the eastern edge of single family dwellings located 250 m to the west.

The LLNL Livermore site has an average wind speed of only 2.5 m s^{-1} and experiences a high frequency of low wind speeds (Gouveia and Chapman 1989). Wind speeds are less than 1 m s^{-1} for 27% of the time and less than 2 m s^{-1} for 50% of the time. Sea breezes predominate during the warm season and are largely responsible for the high annual frequency (~55%) of winds from the southwest through west sectors. Approximately 13% of the winds, mostly very light, blow from the east-northeast through east-southeast sectors and are most affected by the line of eucalyptus trees.

The orientation of the sensors on the 10- and 35-m tower booms is shown in Figure 2. Note that the instrumentation and placement is identical on the two booms except for the sonic anemometer located only on the 10-m boom. The booms are installed toward the west at a distance more than two tower widths away from the open lattice tower to minimize tower effects on measurements. A datalogger (Campbell Scientific CR23X) is connected to and polls all of the instruments at a 1-Hz rate. The datalogger calculates 15-minute averages, standard deviations, and other parameters that are downloaded to a remote server via modem every 15 minutes. Data are automatically assured for quality during real-time, visually scanned daily, and thoroughly checked monthly.

The mechanical wind sensors used to measure wind direction and speed are the Met One 010C wind vane and 020C 3-cup anemometer. The stated accuracy of the wind vane is ±3° and the distant constant (λ) is less than 0.9 m (see Table 1 for specification summary). The cup anemometer is accurate to within ±1% at speeds less than 50 m s^{-1} and λ is less than 1.5 m. An R.M. Young propeller anemometer 27106T measures the vertical wind speed. The vertical propeller is accurate to within ±1% within speeds of ±20 m s^{-1} and λ = 2.1 m. Vertical wind speeds are multiplied by a factor of 1.25 by the datalogger in real time as suggested by the manufacturer. The use of the multiplier brings the vertical anemometer output signal to within ±3% of the cosine response for typical conditions. All sensors have a starting threshold of 0.22 m s^{-1}.

An R.M. Young Model 81000 ultrasonic anemometer was used in this study to measure fast-response wind measurements in three dimensions. The sensor has 3 opposing pairs of ultrasonic transducers that are arranged so that measurements are made through a common volume. The stated wind direction accuracy is ±2° for wind speeds of 1 to 30 m s^{-1}. The wind speed accuracy is ±1% rms ±0.05 m s^{-1} for speeds up to 30 m s^{-1}. The starting threshold during this experiment was the factory set value of 0.2 m s^{-1} although it can be set to as low as 0.01 m s^{-1}.

A high-precision thermistor (Met One 060A-2) and the sonic anemometer measured temperatures side-by-side. The thermistor has a stated accuracy of ±0.1 ˚C and is used to measure precise temperatures and vertical differences. The sonic anemometer is much less accurate and has a stated accuracy of ±2 ˚C.

A year (2004) of 15-minute averaged data measured by the sonic and mechanical wind sensors was analyzed and compared. The following variables and derived parameters are routinely monitored and were analyzed in this study: 15-minute average and peak 1-second (scalar) wind speed (u), standard deviation of longitudinal wind speed fluctuations (σ_u), wind direction (θ) and the standard deviation of its fluctuations (σ_θ), standard deviation of vertical wind speed (σ_w) and wind angle fluctuations (σ_ϕ), air temperature (T), and momentum flux $-\overline{(u'w')}$. Note that the ratio σ_w/u was used to estimate σ_ϕ. Invalid or suspicious data were deleted and not included in the analyses.

3. Results

a. Horizontal wind variables

The correlation of sonic- vs. cup-derived wind speeds is shown in Figure 3. The correlation appears excellent throughout the range of wind speeds. The correlation in this study is slightly better than the agreement found in the studies by Baxter et al. (2003) and Lewis and Dover (2004) which compared wind speeds derived from sonic with propeller anemometers. Note that these previous studies used shorter averaging periods of 5 and 2 minutes, respectively. The peak differences in the cup anemometer from the sonic were +1.0 m s^{-1} and –1.2 m s^{-1}, the 5- and 95-percentile values were –0.08 and 0.25 m s^{-1}, respectively, and the standard deviation was 0.11 m s^{-1}. However, scatter is more apparent at wind speeds less than 2.5 m s^{-1} or so. Figure 4 analyzes the same data by fractional error and more clearly indicates the increased scatter as well as the bias at low speeds. Note the steady increase in scatter as wind speeds decrease. A bias of high wind speeds from the cup anemometer becomes noticeable at speeds (as measured by the cups) less than about 2.5 m s^{-1}. The cup anemometer measures higher speeds than the sonic does for 93% of the time when the cup indicates speeds less than or equal to 2 m s^{-1} and the median bias is 0.13 m s^{-1}. The likely cause of the bias at light wind speeds is the over-speeding by the cup anemometer during variable wind conditions as explained by Wyngaard (1981). While these relatively small errors may be ignored for most users interested in average weather conditions, it will be shown later in the paper that these errors may contribute to large errors in determining widely-used vertical turbulence and dispersion values.

The characteristics of both sensors in estimating wind speed are examined further by comparing measured σ_u values. This variable is also used to estimate dispersion of a puff in the downwind direction. The scatter plot in Figure 5 illustrates that σ_u values show excellent agreement between the cup and sonic anemometer measurements with r^2 = 0.98. Note that the cup anemometer indicates slightly lower σ_u values (~0.06 m s^{-1}) than from the sonic anemometer for wind speeds greater than 3 m s^{-1} (not shown). However, the fractional analysis shown in Figure 6 indicates a similar large bias for σ_u as with wind speed at speeds less than about 2.5 m s^{-1}. The median cup/sonic σ_u ratio increases from 0.94 for all wind speeds to 1.00 and 1.08 for speeds less than 2 and 1 m s^{-1}, respectively.

The distributions in Figures 5 & 6 suggest that the cup anemometer yields slightly higher values but large fractional differences of u and σ_u compared to those measured by the sonic anemometer at low speeds. The bias disappears at speeds above 2 to 2.5 m s^{-1}.

Peak wind gusts (1-sec) were also compared between the cup and sonic anemometer and a scatter plot is shown in Figure 7. The correlation is excellent and virtually the same as for average wind speed. The median cup/sonic ratio of wind gusts is 1.02 for all speeds and increases to 1.07 and 1.13 for wind speed values less than 2 and 1 m s^{-1}, respectively. The plot suggests that the cup anemometer indicates slightly higher speeds than the sonic at speeds greater than 17 m s^{-1} as indicated by the cup anemometer.

An analysis comparing wind direction measured by the co-located wind sensors was also made. A systematic difference of almost 5° for all directions was observed and attributed to slight orientation error of either or both of the sensors. The difference was corrected and the fractional analysis is shown in Figure 8. Note the excellent agreement and the noticeable increase in scatter at wind speeds less than 2 m s^{-1} as measured by the cup anemometer. While the slower response of the wind vane undoubtedly causes errors with light wind speeds below 1 m s^{-1}, measured wind directions may not be meaningful at these wind speeds. Anfossi et al. (2005) point out that meandering (low frequency horizontal wind oscillations) begins to prevail when winds decrease below a certain level (1-2 m s^{-1}) and that it becomes difficult to define a precise wind direction and to predict airborne dispersion. Deaves and Lines (1998) suggest a lower limiting wind speed that ranges from 0.5 m s^{-1} in stable and neutral conditions to 1.2 m s^{-1} in unstable conditions. Wind direction differences were within ±7° and ±5° 90% and 80% of the time, respectively. Wind direction differences exceeded 13° and 23° for 20% and 10% of the time, respectively, when wind speeds were less than 1 m s^{-1}.

Values of σ_θ, often used to estimate the downwind, lateral dispersion and spread of pollutant plumes, were compared between the wind vane and sonic anemometers. Results shown in Fig. 9 indicate a generally good agreement with the median ratio of vane/sonic equal to 1.02 with 90% of values between 0.94 and 1.23 across all wind speeds and an r^2 value of 0.84. However, there are some cases with the vane indicating σ_θ values approaching or reaching zero during very light wind conditions.

The fractional analysis in Figure 10 better illustrates the dramatic change in the ratio of σ_θ values as measured by the wind vane and sonic anemometer. The agreement between the values from the two instruments is very good for wind speeds above 2 m s^{-1}, although the vane yields σ_θ values that are 7% greater than those from the sonic. The bias is consistent with the slower response of the wind vane (i.e., vane overshooting). Scatter increases significantly at wind speeds below 2 m s^{-1} and the relationship between the measurements becomes more complicated at lower speeds. The ratio of vane/sonic σ_θ values tends to spike at average wind speeds of about 0.5 m s^{-1} and then plunge as speeds approach the starting thresholds of the vane and cup. This behavior may result from the less responsive vane yielding excessive variation by overshooting at very light speeds of about 0.5 m s^{-1} and too little variation as speeds diminish toward or even below the starting threshold of 0.22 m s^{-1}.

b. Vertical wind variables and parameters

Median vertical wind speeds for all horizontal wind speeds (not shown) indicate that both the vertical propeller and sonic anemometer indicate virtually no average vertical transport (0.02 and –0.01 m s^{-1}, respectively). The results are consistent with the flat terrain and differences from zero are well within the instrument resolution and possible slight mounting differences from the vertical. The comparison of σ_w values measured by the vertical propeller and sonic anemometers is shown in Figure 11. The correlation is very good with $r^2 = 0.98$. Note that the propeller yields σ_w values about 0.1 m s^{-1} lower than the sonic at low values and about 0.1 m s^{-1} higher than the sonic at higher values. Part of the bias results from the application of the correction factor (1.25) to the propeller for the non-cosine response error: the factor may be too small at low wind speeds and too high at higher wind speeds.

A fractional analysis of the two measurements describes the differences as a function of horizontal wind speed and is shown in Figure 12. Similar to some of the horizontal wind variables previously analyzed, the agreement between the mechanical and sonic sensors deteriorates at lower horizontal wind speeds. Because of the vertical orientation of the mechanical propeller, the breakdown in agreement starts occurring at speeds less than 3 m s^{-1}, at a somewhat higher threshold than for the horizontal wind analyses.

The median propeller/sonic ratio for σ_w values is 0.83 for all wind speeds and it increases to 0.91 for speeds greater than 2 m s^{-1} and it exceeds 1 for wind speeds exceeding about 5.5 m s^{-1}. The median propeller/sonic ratio decreases to only 0.47 and 0.10 at horizontal wind speeds below 2 and 1 m s^{-1}, respectively. The bias is especially large at wind speeds less than 1 m s^{-1}, when the propeller measures σ_{w} values less than 50% of sonic values about 85% of the time. The bias results from the poor response of the propeller during stable conditions and light winds. These results are consistent with a study by Garratt (1975) that indicates the use of a vertical propeller at a 10-m height above ground during stable conditions will lead to underestimation of vertical velocity fluctuations. Finkelstein et al. (1986) suggest that intermittent stalling of the propeller anemometer led to similar underestimation of σ_w and σ_ϕ during stable conditions with light winds during a field study.

The measured σ_w and u values can be combined to estimate σ_ϕ, often used to estimate vertical dispersion and pollutant spread. A regression analysis of σ_ϕ values estimated from the mechanical sensors and the sonic anemometer (not shown) indicates a rather poor linear correlation with an r^2 of only 0.56. The relatively poor correlation is not surprising since σ_ϕ is derived from two separate variables. A fractional analysis of the two σ_ϕ measurements by wind speed is shown in Figure 13. The bias variation for mechanical/sonic σ_ϕ ratios with wind speeds greater than 3 m s^{-1} is similar to the σ_w analysis in Figure 12: the median cup&prop/sonic ratio for σ_ϕ values is 0.78 for all wind speeds and it increases to 0.88 for speeds greater than 2 m s^{-1} and it exceeds 1 for wind speeds exceeding about 6 m s^{-1}. The bias of σ_ϕ values at lower speeds is somewhat worse than for σ_w: the median cup&prop/sonic ratio decreases to only 0.42 and 0.08 at horizontal wind speeds below 2 and 1 m s^{-1}, respectively. The bias is especially large at wind speeds less than 1 m s^{-1}, when the propeller-measured σ_ϕ values are less than 50% of sonic values 90% of the time. The somewhat greater bias σ_ϕ relative to σ_w values at low wind speeds results from the contribution of over-speeding by the cup anemometer (i.e., larger *u* values will cause smaller σ_ϕ values).

The average diurnal variation during July (2004) of *u*, σ_w, and σ_ϕ shown in Fig. 14 illustrates further the differences between the sonic and the mechanical sensors as well as the variation in wind speed and vertical turbulent parameters. Skies were clear during most if not the entire month as is typical during summer months in the region (not shown). Wind speed reaches a maximum during late afternoon as a result of deep thermal instability and frequent occurrence of sea breezes. Note that cup anemometer shows slightly higher wind speeds than the sonic as it tends to over speed during very light wind. The differences in σ_w measurements are noticeable in the early morning as the propeller underestimates by almost 25% on average, Note that the underestimation becomes greater (or less) during periods with lower (or higher) than average wind speeds. The σ_w values as measured by propeller abruptly approach those measured by the sonic shortly after sunrise until early evening, when the propeller again indicates lower values. The largest differences in measurements can be seen with σ_ϕ as the mechanical sensors underestimate by about 50% on average during early morning compared to the sonic. While the underestimation is reduced after sunrise, σ_ϕ values derived from mechanical sensors don't approach those from the sonic until almost noon. The bias in σ_ϕ reappears during the evening.

Momentum flux values were also calculated by calculating covariances of 1-second measurements of *u* and *w* $(-\overline{u'w'})$ using the cup anemometer with the propeller anemometer and components measured by the sonic anemometer. The scatter plot is shown in Figure 15. Note that positive values indicate downward transport and negative values indicate upward transport of momentum. The correlation is excellent (r^2 = 0.86) especially considering that two variables contribute to $-\overline{u'w'}$. Note that the regression line indicates that the mechanical sensors tend to yield absolute values approximately 15% more than from the sonic anemometer for larger positive and negative (upward and downward) values. A fractional analysis by wind speed (not shown) indicates that the median ratio of cup&propeller/sonic ratios of $-\overline{u'w'}$ values decreases from 0.74 for all speeds to 0.42 at less than 2 m s^{-1} and close to 0 for speeds less than 1 m s^{-1}. These results once again point out that the mechanical sensors lack the responsiveness necessary to provide good results at very light wind speeds. Table 2 summarizes the results for wind and turbulent parameters.

b. Temperatures

Temperatures measured by the precise thermistor and the sonic anemometer were analyzed and their correlation is shown in Figure 16. The agreement is excellent throughout the typical temperature range experienced at LLNL. Note that in contrast to the variables and parameters compared previously, the thermistor provides the most accurate temperatures while the sonic anemometer is considerably less accurate. The median absolute error for all wind speeds is 0.23 ˚C and it increases from 0.12˚ for $u < 1$ m s^{-1} to 0.33 ˚C for $u > 2$ m s^{-1}. The peak absolute error for all valid cases was 2.4 ˚C and the 95-percentile values were 0.6°, 0.8°, and 1.3 °C for $u < 1$ m s^{-1}, $u < 2$ m s^{-1}, and $u \geq 2$ m s^{-1}, respectively (not shown).

4. Sonic Anemometer Limitations

The advantages of using sonic anemometers are shown in this and other studies, but they do have several drawbacks. Gilhousen (2001) determined in a study that wind speed values from 2-D sonic anemometers closely correlated with those from a vane and propeller anemometer at to coastal and one buoy site under "normal" conditions (speeds < 15 m s^{-1}). The sonic anemometer however reported wind speeds about 10% higher than from the vane and propeller anemometer during gale winds. In addition, the study revealed that the sonic anemometer occasionally gave unrealistically high speeds and erroneous directions during thunderstorms at coastal stations. While thunderstorms are infrequent in this study area, the sonic anemometer did produce unrealistic wind measurements during and after rainfall or fog because of the wetting of the probes. The percentage loss of 15-minute averages during the year ranged from slightly less than 1% of horizontal and vertical speeds and standard deviations to 0.4% for σ_θ and 0.2% for wind direction. Loss of sonic temperature data occurred during 1.3% of the time.

Note that approximately 1.5% of all 15-minute periods during the year received measurable precipitation. There was a tendency for data loss to be greater during and after rainfalls with light winds.

Another drawback of the 3-D sonic anemometer is its relatively large power requirement. The sonic anemometer requires 110 mA at 12 to 24 VDC, nearly 10 times what the cup anemometer and wind vane individually require and nearly 20 times what the vertical propeller requires. Since the power requirements of the sonic anemometer and radiation shields that ventilate the temperature and relative humidity sensors would drain a battery backup quickly if the tower experienced an AC power loss, they would be automatically switched off until AC power is restored.

5. Conclusions

The low-cost 3-D anemometer has reliably measured the 3 components of wind during an entire year during this study. Data from the sonic anemometer and mechanical wind sensors were analyzed and compared. Results indicate that 15-minute averaged horizontal wind variables (wind speed or u, σ_u, wind direction [θ], and σ_θ) and peak wind gusts measured by mechanical sensors agree well with those measured by an inexpensive 3-D sonic anemometer for wind speeds above 2 to 2.5 m s^{-1}. The mechanical sensors (cup anemometer and wind vane) typically produce σ_u and σ_θ values about 5% lower and higher, respectively, than from the sonic anemometer at these stronger speeds. The agreement between measured vertical wind variables and parameters (w, σ_w, σ_ϕ, and $-\overline{u'w'}$) was also very good above a slightly higher threshold of 3 m s^{-1} or so. The vertical propeller typically measures σ_w and σ_ϕ values about 10% lower than the sonic anemometer with wind speeds of 2.5 to 4 m s^{-1} and about 10% higher at wind speeds above about 6.5 m s^{-1}. Sonic temperature is also shown to be within ±1 °C of the more precise thermistor about 90% of the time.

The advantage of the sonic anemometer becomes increasingly obvious as winds become light and the mechanical sensors become less responsive. The cup anemometer produces values that increasingly overestimate *u* and σ_u compared to the sonic anemometer on a fractional basis as wind speed decreases below 2 m s^{-1}. The difference in wind direction between the vane and sonic measurements becomes large at speeds below 1 m s^{-1}; however, it is difficult to determine the contribution from inadequate wind vane response. The effect of inadequate vane response on σ_θ measurements is more complicated as the vane increasingly overestimates on a percentage basis as horizontal wind speeds decrease below 2.5 m s^{-1}, reaching a maximum at about a 0.5 m s^{-1} wind speed before it underestimates as speeds approach calm.

The most significant differences are associated with the standard deviation of vertical wind fluctuations (σ_w): the co-located vertical propeller anemometer yields values increasingly less than those measured by the sonic anemometer as horizontal wind speeds decrease from 2.5 to near 0 m s^{-1}. The underestimation of σ_w by the vertical propeller and to a lesser extent *overestimation* of *u* by the cups at low wind speeds compounds the errors for the standard deviation of vertical wind angle fluctuations, σ_ϕ, an indicator of vertical dispersion that is often used to calculate the Pasquill-Gifford (P-G) stability category. The sonic anemometer routinely indicates larger σ_ϕ values than the vertical propeller/cup anemometer with the sonic anemometer values typically 5° to 10° higher when the propeller/cup indicate σ_ϕ is less than about 5°. The errors in the propeller anemometer, caused by its inability to capture the higher frequency (smallest scale) turbulent fluctuations, could therefore lead to large (factors of 2 to 10 or more) errors in vertical dispersion estimates during stable conditions with light winds. The sonic anemometer also provides more reliable momentum flux data during light winds.

The drawbacks of the sonic anemometer include invalid or lost data from wetting during or after rainfall or fog and relatively large power requirements from a battery backup if the tower experienced an AC power loss. In spite of its drawbacks, this instrument is ideally suited to supplement routine wind measurements by equaling or improving most measurements from traditional mechanical sensors, especially in the vertical during light winds, and simultaneously providing low-maintenance redundant instrumentation during dry conditions.

6. Further Study

Routine calculations of fifteen-minute averages of vertical heat flux and latent heat (and evaporation) have been made for the past two years at the Livermore tower site using the eddy correlation method with covariances of *w* and *T* (temperature) from the sonic anemometer and *w* from the sonic and *q* (specific humidity) measured by a co-located fast-response hygrometer. Both these fluxes have also been calculated with identical instrumentation at LLNL's experimental test site (Site 300), located approximately 20 km east of the Livermore site. Data loss from wetting is less at this site where the average annual wind speed is approximately 5.5 m s^{-1}, or more than twice than the average speed at the Livermore site. Both sonic anemometers will have their transducers coated with material that sheds water by the manufacturer in hope that data loss from wetting is reduced if not eliminated.

Acknowledgments.

The author thanks Art Biermann and Gretchen Gallegos for their support for the meteorological monitoring program and Gary Bear for his effort in maintaining and improving the meteorological monitoring. The author also thanks Dennis Lundy of Western Weather Group, LLC for setting up the sonic anemometer and its data collection. The helpful comments by Charlene Grandfield are greatly appreciated.

This work was conducted under the auspices of the U.S. DOE by the University of California under contract No. W-7405-Eng-48.

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List of Figures

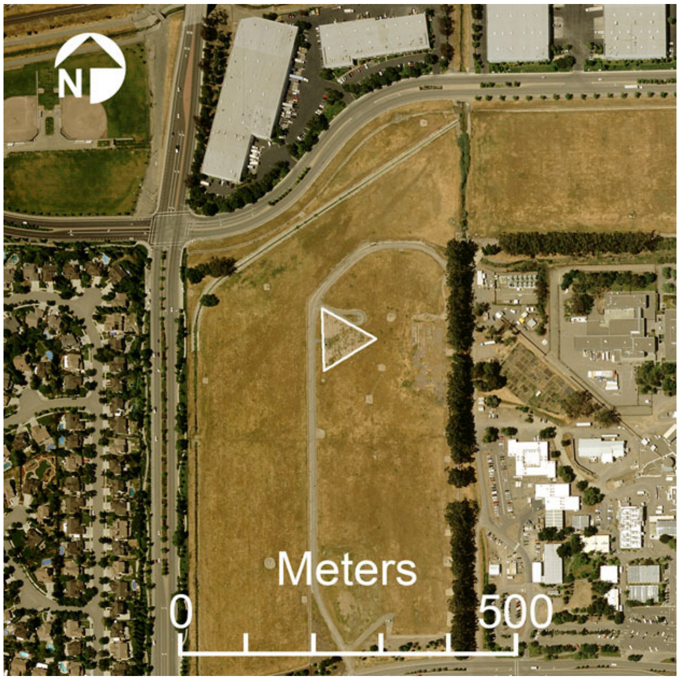

FIG. 1. Aerial photograph of tower (in middle) and surrounding area.

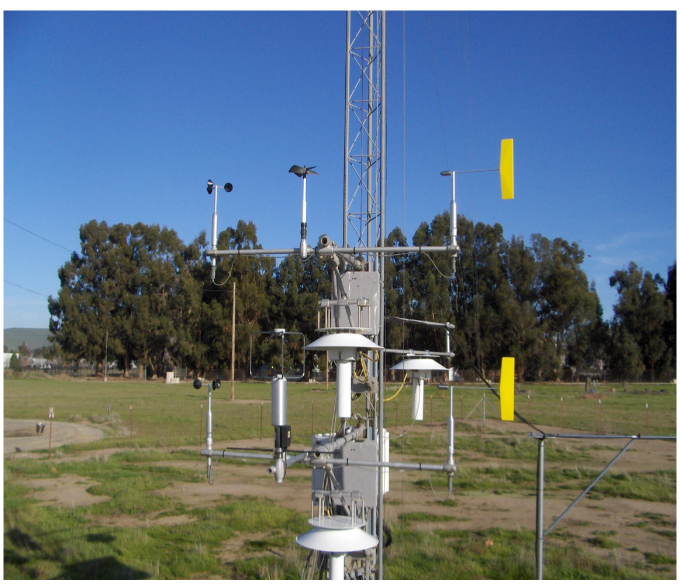

FIG. 2. Wind sensor orientation.

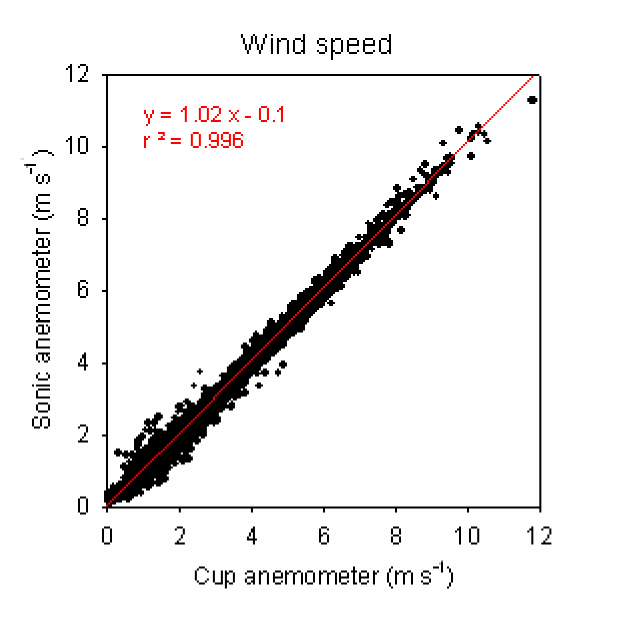

FIG. 3. Regression analysis of 15-minute average wind speeds as measured by cup vs. sonic anemometers.

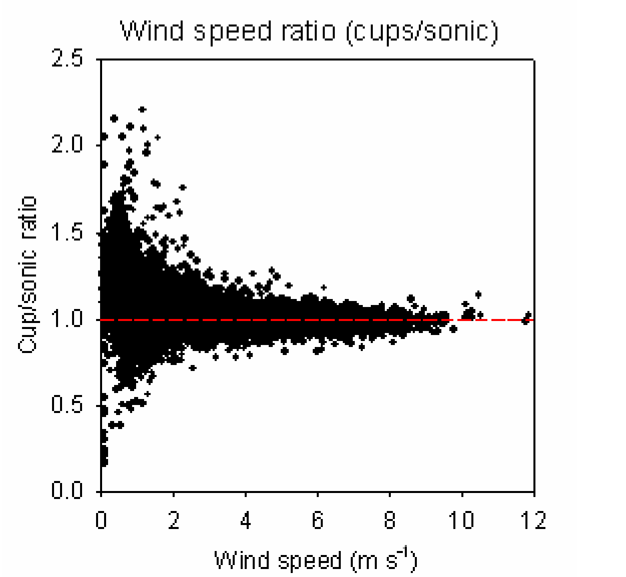

FIG. 4. Ratio of cup/sonic anemometer-derived wind speed as a function of wind speed as measured by the cup anemometer.

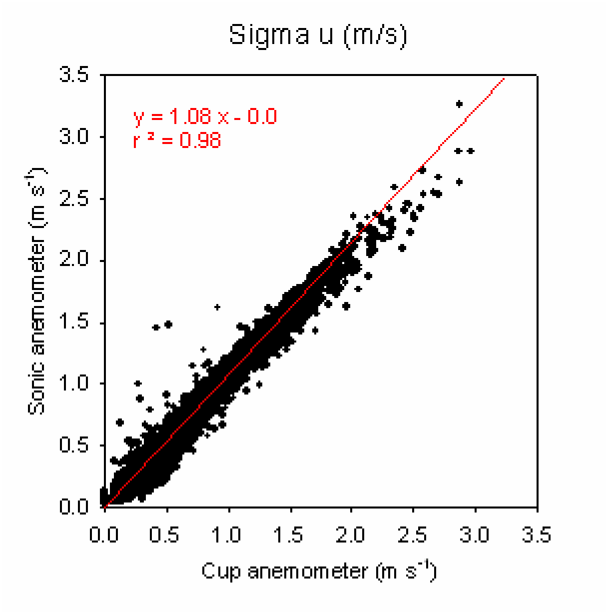

FIG. 5. Same as Figure 3 except for σ_u.

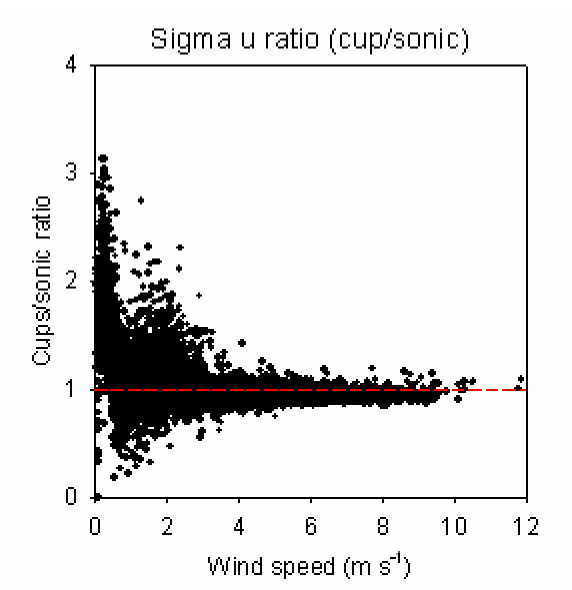

FIG. 6. Same as in Fig. 4 except for σ_u.

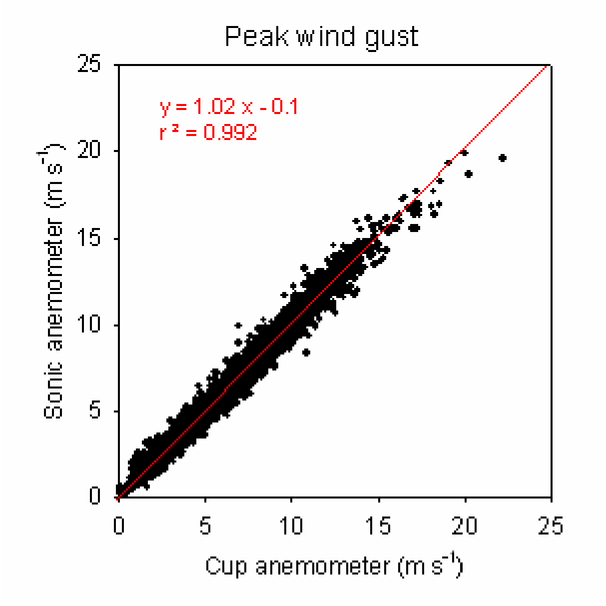

FIG. 7. Same as in Fig. 3 except for peak wind gusts.

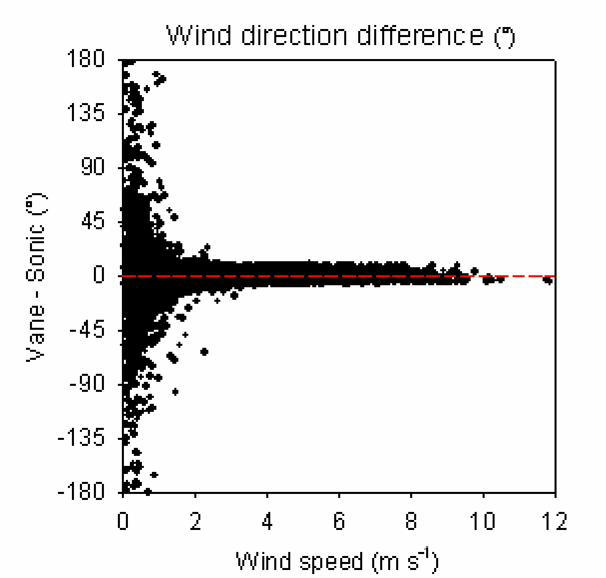

FIG. 8. Difference in vane- and sonic- derived wind direction as a function of wind speed as measured by the cup anemometer.

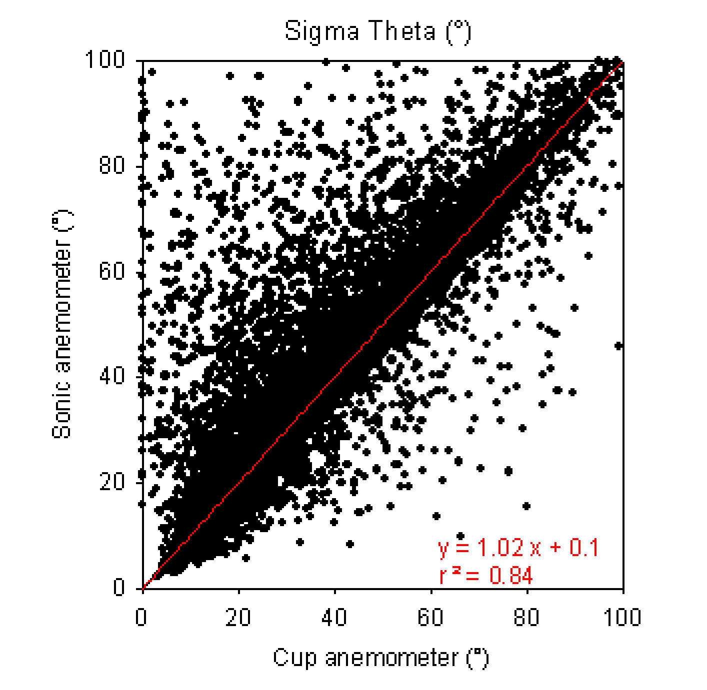

FIG. 9. Same as in Fig. 3 except for σ_θ.

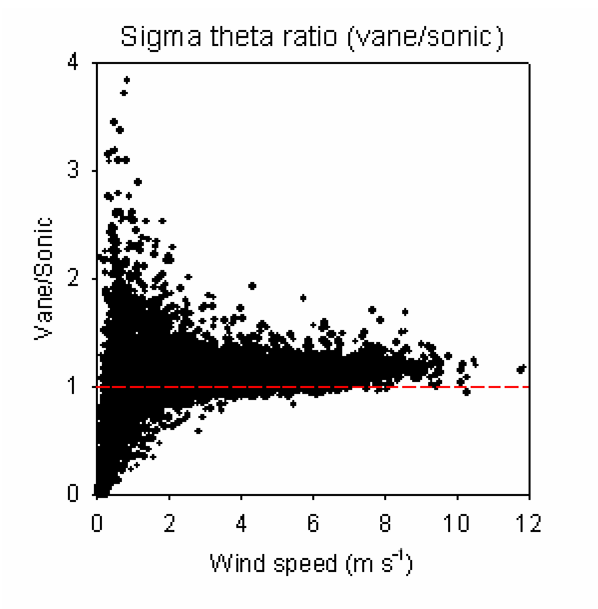

FIG. 10. Same as in Fig. 4 except for σ_θ.

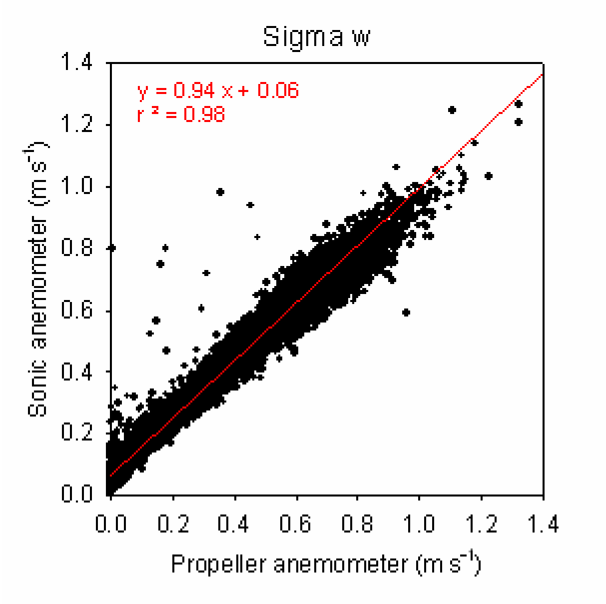

FIG. 11. Same as in Fig. 3 except for σ_w.

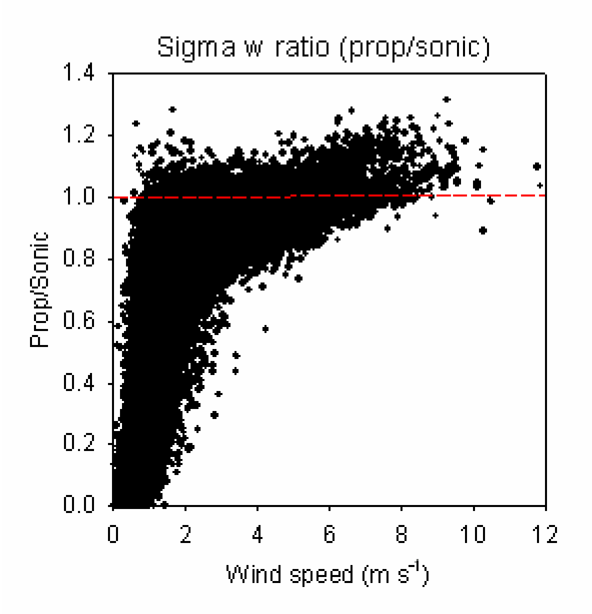

FIG. 12. Same as in Fig. 4 except for σ_w.

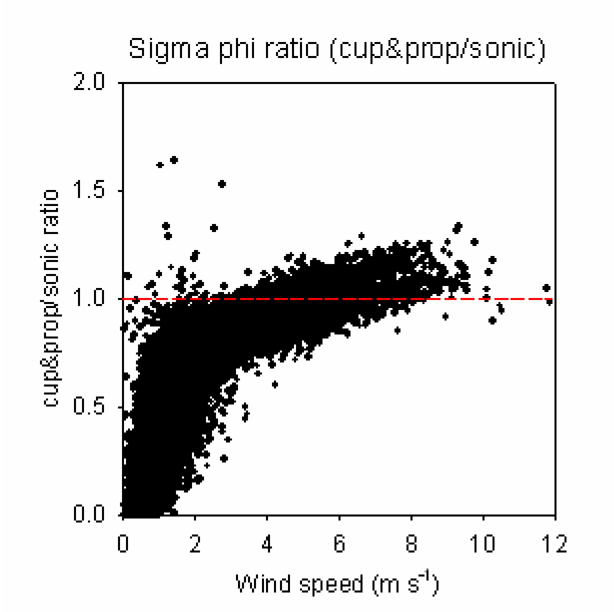

FIG. 13. Same as in Fig. 4 except for σ_w.

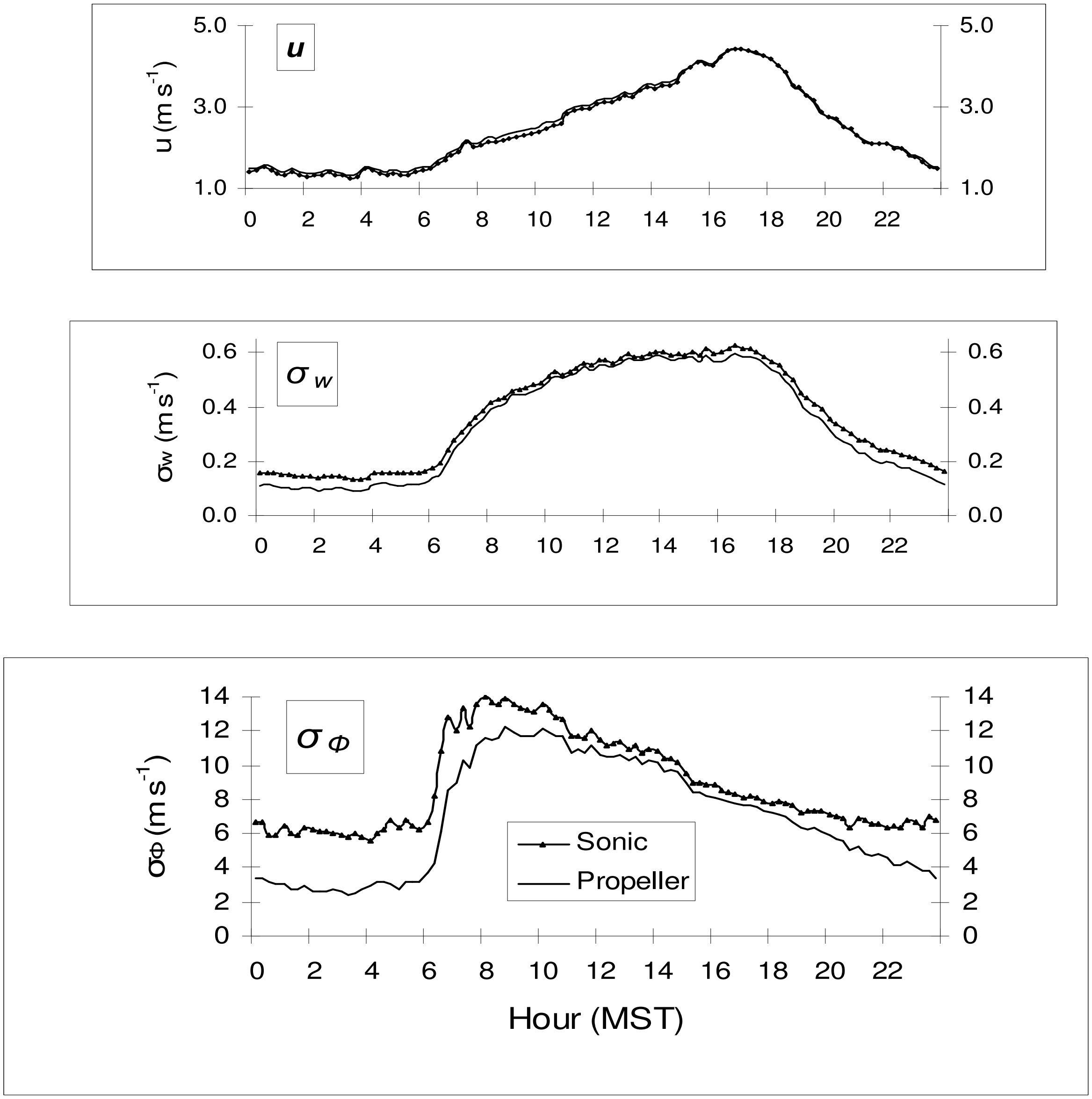

FIG. 14. Averaged 15-minute values of u, σ_w, and σ_ϕ measured by the sonic anemometer and mechanical sensors (cup and propeller anemometers) during July 2004.

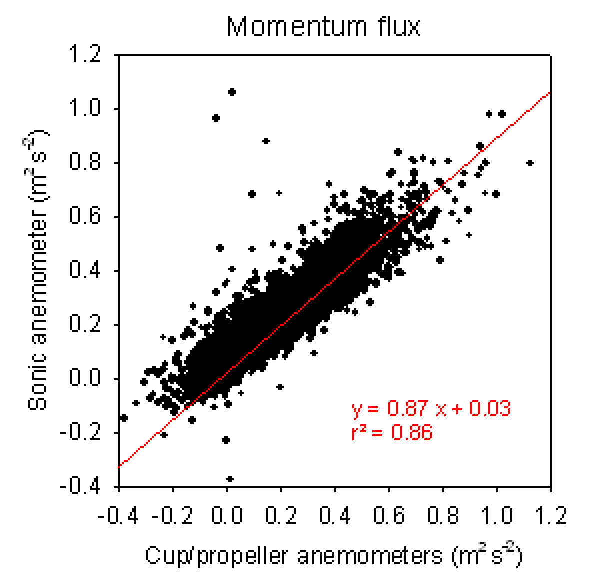

FIG. 15. Same as in Fig. 4 except for $-\overline{u'w'}$.

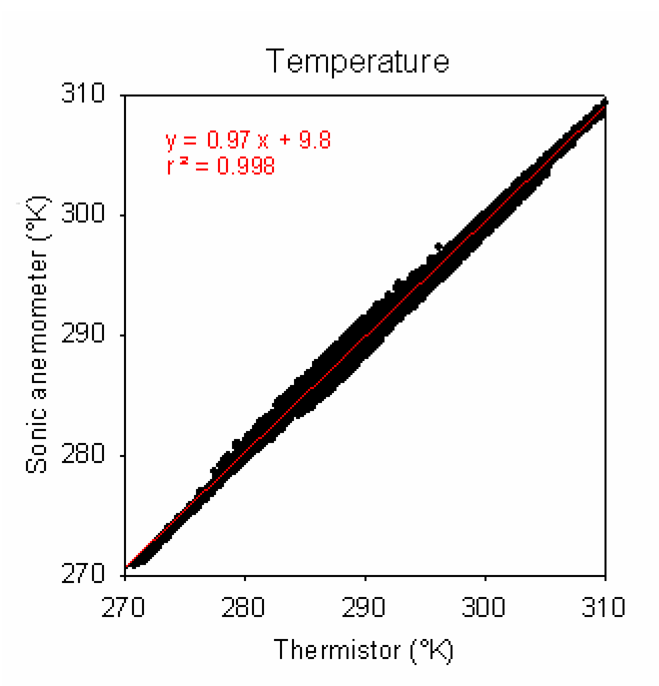

FIG. 16. Same as in Fig. 4 except for temperature.

List of Tables

TABLE 1. Summary of instrument specifications.

Wind Instrument:	Accuracy	λ (m)	Starting threshold (m s^{-1})
Wind vane	± 3°	< 0.9	0.22
Cup anemometer	± 1%	< 1.5	0.22
Vertical propeller	± 1%	2.1	0.22
Sonic anemometer	±1% rms ±0.05 m s^{-1}	~ 0	0.20
Thermometer:	Accuracy (°C)		
Sonic anemometer	± 2°		
Thermistor	± 0.1°		

TABLE 2. Summary of results.

Variable/ parameter	r^2	Median Mechanical Sensors/Sonic ratio			
		All winds	≥2 m s^{-1}	<2 m s^{-1}	<1 m s^{-1}
Wind speed (u)	0.966	1.06	1.03	1.16	1.24
Peak wind gust	0.922	1.02	1.00	1.07	1.12
Sigma u (σ_u)	0.98	0.95	0.94	0.98	1.08
Sigma theta (σ_θ)	0.84	1.05	1.07	1.00	0.94
Sigma w (σ_w)	0.98	0.83	0.91	0.47	0.10
Sigma phi (σ_ϕ)	0.56	0.78	0.88	0.42	0.08
Momentum flux ($-\overline{u'w'}$)	0.86	0.74	0.89	0.02	0.00
		80-percentile absolute θ error (˚)			
Wind direction (θ)		5.2	4.9	7.1	13.2
		Median absolute T error (˚K)			
Temperature (T)		0.23	0.33	0.15	0.12