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

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1. INTRODUCTION

Inexpensive 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 (e.g., see Baxter et al. 2003 and Vidal and Yee 2003).

This paper describes the results of comparing horizontal winds and 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 the 40-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

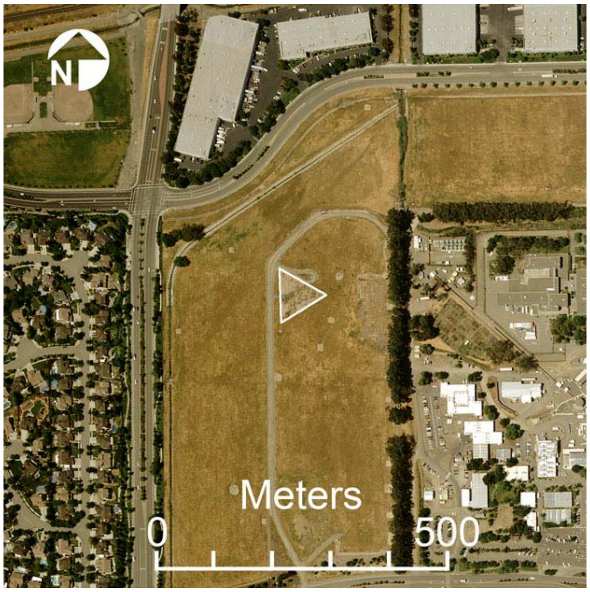

Figure 1. Aerial photograph of tower (in middle) and surrounding area.

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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 and experiences a high frequency of low wind speeds (Gouveia and Chapman 1989). Wind speeds are less than 1 m/s for 27% of the time and less than 2 m/s 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 40-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.

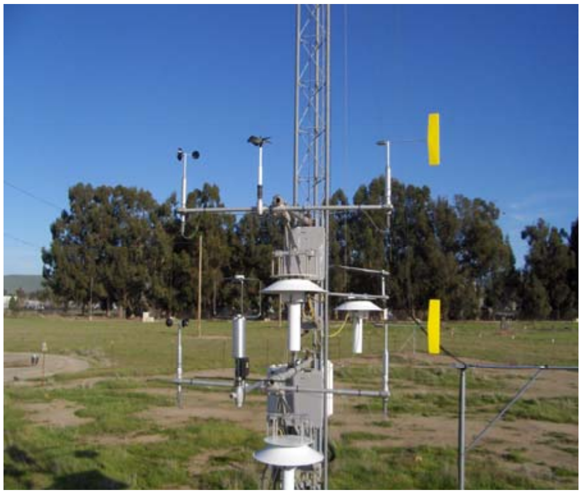

Figure 2. Wind sensor orientation.

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 is less than 0.9 m. The cup anemometer is accurate to within ±1% at speeds under 50 m/s and the distant constant is less than 1.5 m. An R.M. Young propeller anemometer 27106F measures the vertical wind speed. The vertical propeller is accurate to within ±1% within speeds of ±20 m/s and has a distant constant of 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.

An R.M. Young Model 8100 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. The wind speed accuracy is ±1% rms ±0.05 m/s for speeds up to 30 m/s. The starting threshold during this experiment was the factory set value of 0.2 m/s although it can be set to as low as 0.01 m/s.

A year of 15-minute averaged data (2004) 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), and vertical momentum flux $-(\overline{u'w'})$. Note that the ratio σ_w/u was used to approximate σ_ϕ. Invalid or suspicious data were deleted and not included in the analyses.

3. RESULTS

3.1 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) that 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 and –1.2 m/s, the 5- and 95-percentile values were –0.08 and 0.25 m/s, respectively, and the standard deviation was 0.11 m/s. However, scatter is more apparent at wind speeds less than 2.5 m/s or so. Figure 4 analyzes the same data by fractional error and more clearly indicates the increased scatter as well as 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 clear at speeds (as measured by the cups) less than about 2.5 m/s. 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 and the median bias is 0.13 m/s. 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. A scatter plot of σ_u values (not shown) shows excellent agreement between the cup and sonic anemometer with r^2 = 0.98. Note that the cup anemometer indicates slightly lower values (~0.06 m/s) than from the sonic anemometer for wind speeds greater than 3 m/s. However, the fractional analysis shown in Figure 5 indicates a similar large bias for σ_u as with wind speed at speeds less than about 2.5 m/s. The median cup/sonic σ_u ratio

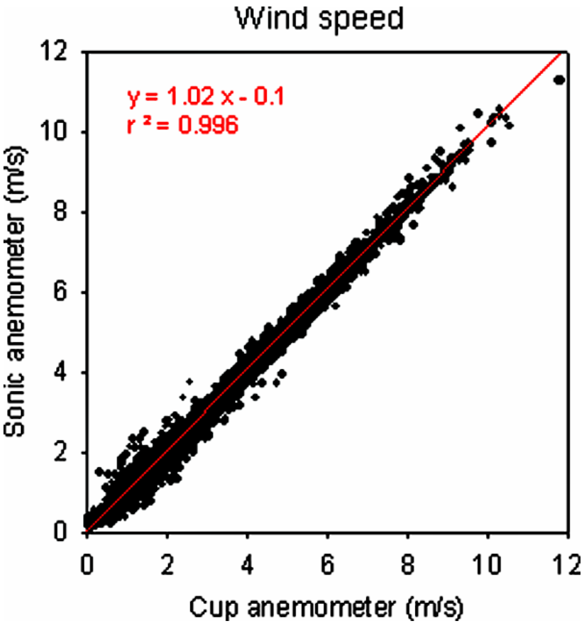

Figure 3. Regression analysis of 15-minute average wind speeds as measured by cup vs. sonic anemometers.

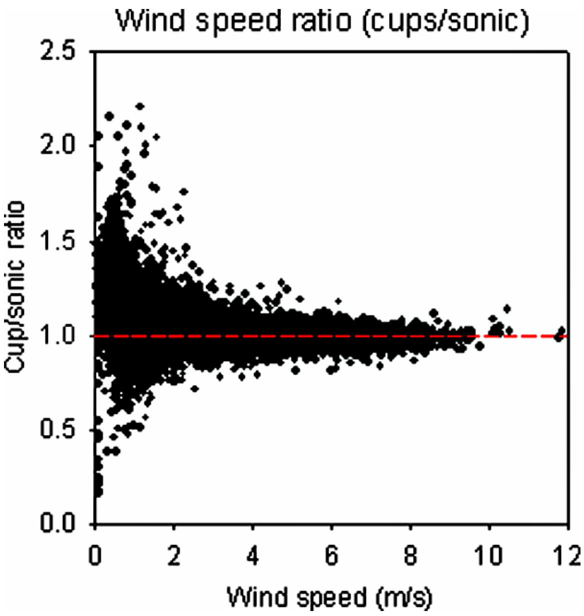

Figure 4. Ratio of cup/sonic anemometer-derived wind speed as a function of wind speed as measured by the cup anemometer.

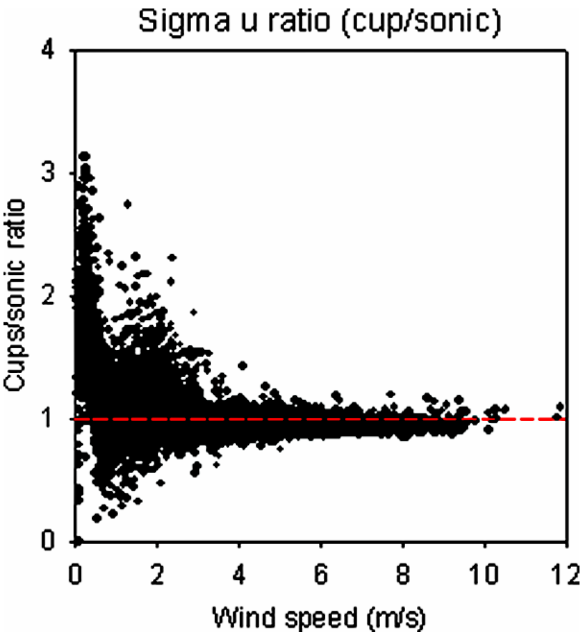

Figure 5. Same as Figure 4 except for σ_u.

increases from 0.94 for all wind speeds to 1.00 and 1.08 for speeds less than 2 and 1 m/s, respectively. The distributions in Figures 4 & 5 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.

Peak wind gusts (1-sec) were also compared between the cup and sonic anemometer and a scatter plot is shown in Figure 6. 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, respectively. The plot indicates that the cup anemometer indicates slightly higher speeds than the sonic at speeds greater than 17 m/s 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 7. Note the excellent agreement and the noticeable increase in scatter at wind speeds less than 2 m/s as detected by the cup anemometer. Wind direction differences were within ±7° and ±5° 90% and 80% of the time, respectively. Wind direction differences exceeded 13° and 23° 20% and 10% of the time, respectively, when wind speeds were less than 1 m/s.

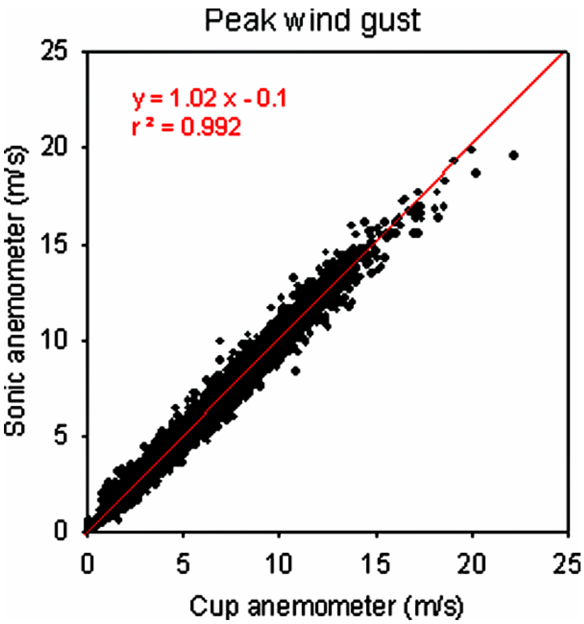

Figure 6. Same as Figure 3 except for peak wind gusts.

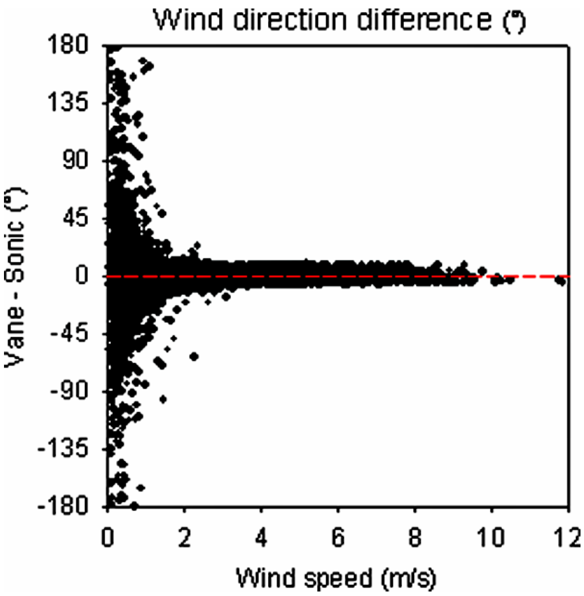

Figure 7. Difference in vane- and sonic- derived wind direction as a function of wind speed as measured by the cup anemometer.

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 (not shown) indicate a very 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, the fractional analysis in Figure 8 indicates that the amount of agreement varies dramatically with wind speed. The agreement between the two instruments is very good for wind speeds above 2 m/s, 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. Scatter increases significantly at wind speeds below 2 m/s 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 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 at very light speeds of about 0.5 m/s and too little variation as speeds diminish toward or even below the starting threshold of 0.2 m/s.

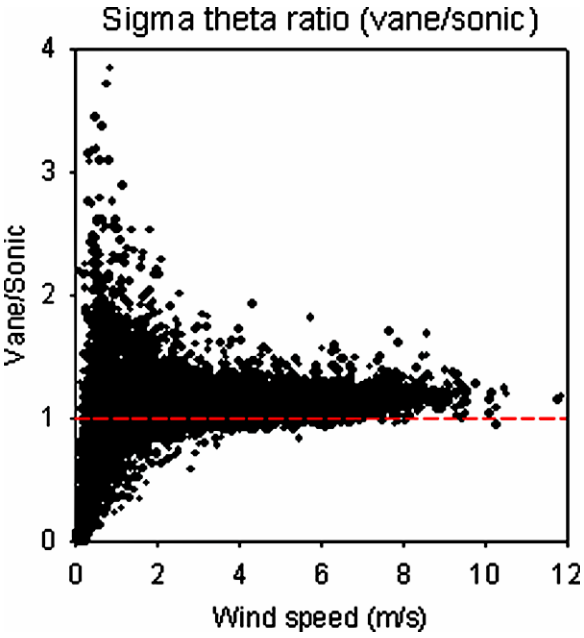

Figure 8. Same as figure 4 except for σ_θ.

3.2 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, 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 9. The correlation is very good with r^2 = 0.98. Note that the propeller yields σ_w values about 0.1 m/s lower than the sonic at low values and about 0.1 m/s 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 10. 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, at a somewhat higher threshold than for the horizontal wind analyses.

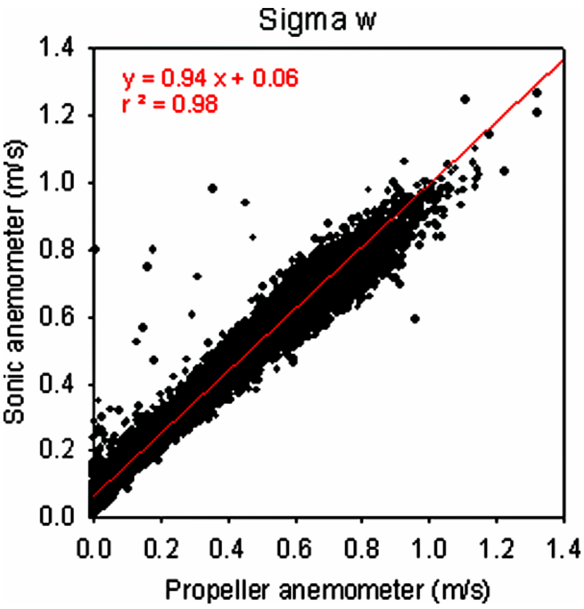

Figure 9. Same as Figure 3 except for σ_w.

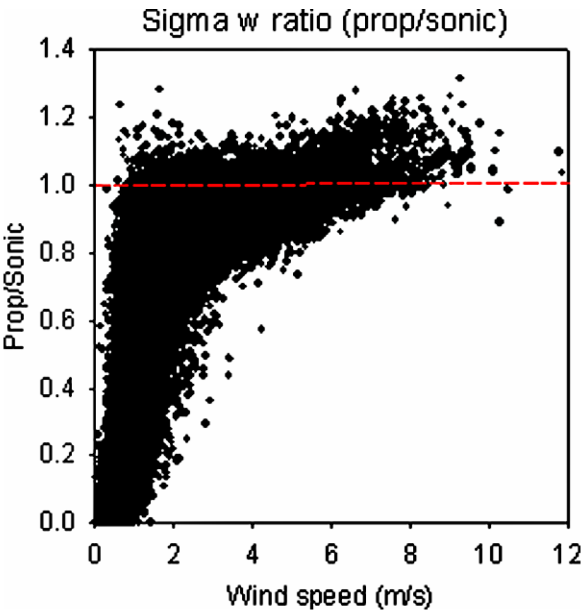

Figure 10. Same as Figure 4 except for σ_w.

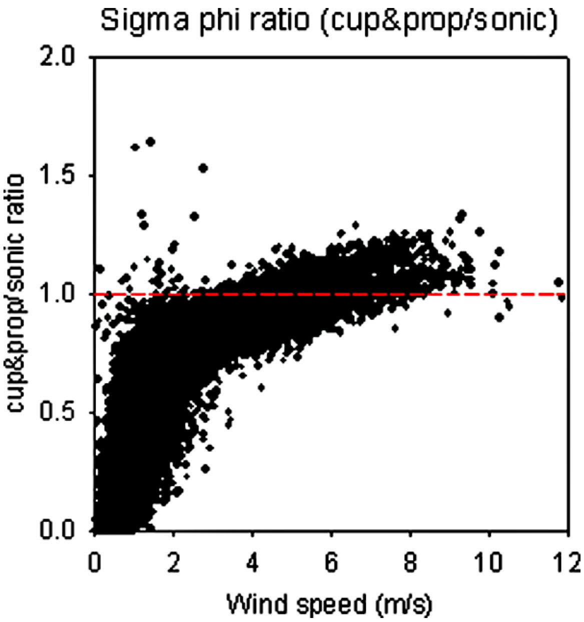

Figure 11. Same as Figure 4 except for σ_ϕ.

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 and it exceeds 1 for wind speeds exceeding about 5.5 m/s. The median propeller/sonic ratio decreases to only 0.47 and 0.10 at horizontal wind speeds below 2 and 1 m/s, respectively. The bias is especially large at wind speeds less than 1 m/s, 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 light wind (and stable) conditions. These results are consistent with a study by Garratt (1975) that indicates that the use of a vertical propeller at a 10-m height above ground during stable conditions will lead to underestimation of vertical velocity fluctuations.

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. A fractional analysis of the two measurements by wind speed is shown in Figure 11. The bias variation for mechanical/sonic σ_ϕ ratios with wind speeds greater than 3 m/s is similar to the σ_w analysis in Figure 10: 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 and it exceeds 1 for wind speeds exceeding about 6 m/s. 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, respectively. The bias is especially large at wind speeds less than 1 m/s, when the propeller-measured σ_ϕ values are less than 50% of sonic values 90% of the time. The somewhat higher difference of σ_ϕ relative to σ_w values at low wind speeds may result from the contribution of over-speeding by the cup anemometer at low wind speeds (i.e., larger u values will cause smaller σ_ϕ values).

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 12. 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

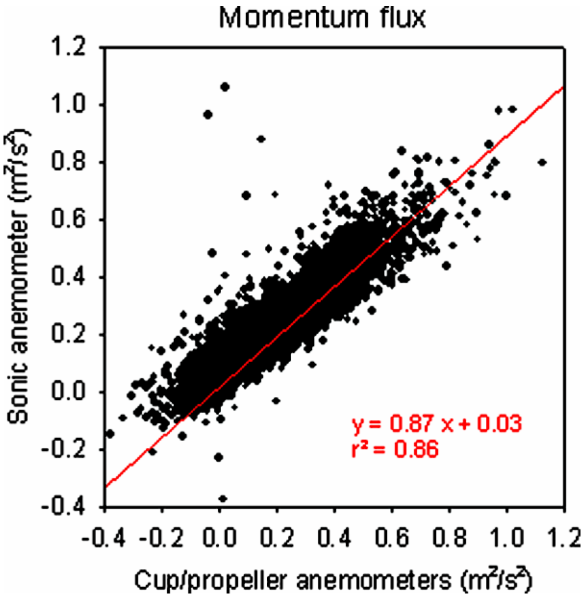

Figure 12. Same as Figure 3 except for $-\overline{u'w'}$.

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 and close to 0 for speeds less than 1 m/s. These results once again point out that the mechanical sensors lack the responsiveness necessary to provide good results at very light wind speeds. Table 1 summarizes the study results.

Table 1. Summary of results

Variable/ parameter	r^2	Median Mechanical Sensors/Sonic ratio			
		All winds	≥2 m/s	<2 m/s	<1 m/s
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

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 two coastal and one buoy site under “normal” conditions (speeds < 15 m/s). However the sonic anemometer 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. 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 or 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. 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 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 and about 10% higher at wind speeds above about 6.5 m/s.

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. The difference in wind direction between the vane and sonic measurements becomes large at speeds below 1 m/s; 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, reaching a maximum at about a 0.5 m/s 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. The underestimation of σ_w by the vertical propeller and to a lesser extent 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 using the covariance of w and T (temperature) from the sonic anemometer have started recently. Routine calculations of fifteen-minute averages of vertical evaporative heat fluxes (and evaporation) using the sonic anemometer and a co-located fast-response hygrometer using the eddy correlation method have also started recently. Real-time removal of high-frequency data spikes from the sonic anemometers will be investigated in order to reduce spurious data, especially during wet conditions.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Baxter, R.A., D.L. Yoho and K.R. Durkee, 2003: Quality assurance audit program for surface and upper-air meteorological measurements in the south coast air basin in California; 12th Symp. on Meteorological Observations and Measurements, February 1-13, Amer. Meteor. Soc., Long Beach, CA, Session 6.5.

Garratt, J.R., 1975: Limitations of the eddy-correlation technique for the determination of turbulent fluxes near the surface, *Boundary Layer Meteorol*., 8, 255-259.

Gouveia, F.J. and K.R. Chapman, 1989: Climatology of Lawrence Livermore National Laboratory, UCID-21686, Lawrence Livermore National Laboratory, Livermore, CA.

Gilhousen, D.B., 2001: An evaluation of Gill sonic anemometers in the marine environment; 11th Symp. on Meteorological Observations and Measurements, January 14-18, Amer. Meteor. Soc., Albuquerque, NM, 35-39.

Lewis, R. and J.M. Dover, 2004: Field and operational tests of a sonic anemometer for the automated surface observing system; 8th Symp. on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface, January 11-15, Amer. Meteor. Soc., Seattle, WA, Session 7.1.

Vidal, E. and Y. Yee, 2003: Data collection of high resolution 3D sonic anemometer measurements; 19th International Conference on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, February 1-13, Amer. Meteor. Soc., Long Beach, CA, Session P1.5.

Wastrack, K.G., D.E. Pittman, and L.W. Hamberger, 2001: Wind sensor comparison-ultrasonic versus wind vane/anemometer; 11th Symp. on Meteorological Observations and Measurements, January 14-18, Amer. Meteor. Soc., Albuquerque, NM, 29-34.

Wyngaard, J.C., 1981: Cup, propeller, and sonic anemometers in turbulence research, *Ann. Rev. Fluid Mech*, 13, 399-423.