A correction for sonic temperature errors resulting from flow acceleration and sensor head distortion

H.1 Abstract

The correction of temperature measurements derived from sonic anemometry is reviewed. Additional terms are incorporated which adjust sensible heat fluxes derived from sonic temperature for flow acceleration and sensor head distortion. Respectively, these additional terms produce an adjustment to sensible heat flux of $-4.8 \pm 15.6 \text{ W m}^{-2}$ and $+7.5 \pm 19.2 \text{ W m}^{-2}$, for the data set tested. These compare with the standard adjustment for the fluctuations of water vapour and sensor path deflection of $-7.3 \pm 13.9 \text{ W m}^{-2}$. When these corrections are combined the resulting net adjustment of $+2.7 \pm 13.7 \text{ W m}^{-2}$ is observed.

H.2 Introduction

Sonic anemometers have simplified the field of micrometeorological flux measurement. They provide a durable and precise instrument with which the velocity signals required to calculate fluxes of both momentum and scalar quantities. A number of sensor configurations have been established in order to minimise weaknesses in the inherent design restrictions (Kaimal and Finnigan, 1994). Even so, most sonic anemometer designs allow for the measurement of all three wind component vectors within close proximity, and at a frequency greater than those at which most flux density exists. These measurement capabilities and the desirable quality of minimal user maintenance have resulted in widespread use of this sensor as a primary, eddy covariance measurement device.

Although sonic anemometers provide an excellent platform for measuring the fluxes of momentum, additional sensors are required to measure the fluxes of scalars. Such sensors must be installed in close proximity to the sonic
anemometer in order to avoid loss of higher frequency signals due to sensor separation (Moore, 1986). The distance within which such a sensor may be mounted is limited by its potential for alteration of the wind velocity components and mounting practicalities. Temperature constitutes a primary measurement because it determines the flux of sensible heat, which is a component of the energy budget as well as numerous derived variables and correction terms. Because of this importance, its accurate measurement is critical. Temperature is often measured with the use of fine-wire thermocouples (TC), platinum resistance thermometers (PRT), or derived from measurements of the speed of sound. While accurate temperature measurements can be made with both thermocouples and platinum resistance thermometers, they are both subject to effects of thermal inertia and solar heating at low wind speeds and are prone to breakage at high wind speeds (Jacobs and McNaughton, 1994), (Kaimal and Finnigan, 1994). In addition, precipitation interception and condensation/rime can alter their response characteristics (Schmitt K.F. et al., 1978), (Lawson and Cooper, 2001).

Sonic temperature measurements exploit the dependence of the speed of sound on the density, and hence temperature, of the air through which the sound travels. Because a sonic anemometer measures the travel times of sound pulses through air, it provides the ideal sensor with which to measure speed of sound derived air temperature. It has been pointed out that the resulting temperature measurement must be corrected to obtain a true air temperature (Schotanus et al., 1983). Errors in the measurement of sonic temperature due to deflection of the sound path and variations in the air density as a result of water vapour fluctuations have been described and correction values presented in earlier works on this subject (Schotanus et al., 1983) (Kaimal and Gaynor, 1991), (Hignett, 1992).

In addition to the now standard corrections to sonically derived temperature for advective sonic path lengthening and density fluctuations, Grelle & Lindroth (1996) have observed a wind speed related error. They observed, for a Gill Solent anemometer under high wind speeds, that sensible heat fluxes determined using sonic temperature were more negative than those
determined using a PRT. Their evidence demonstrates that the difference between the sonic and PRT temperatures occurred at all frequencies. They also show that this error persists in cospectra, implying that it is well correlated with vertical velocity. Their compiled fluxes for a distribution of wind speeds show a wind velocity threshold of about 7 m/s, above which the error in sensible heat flux was increasingly more pronounced. The authors also state that similar errors, with similar thresholds, were observed in other research with METEK, and Kaijo Denki anemometers. They conclude that the error resulted from deformation of the sonic anemometer’s sensor head under high wind speeds and suggest that wind tunnel tests are required to ascertain an appropriate correction term.

We have observed similar differences in the comparison of sensible heat fluxes obtained using sonic, $H_s$, and thermocouple, $H_{tc}$, temperature measurements. Coincident high wind speeds suggested that this difference was also the result of the deformation of the sonic anemometer’s head. In this paper we present further evidence in support of this hypothesis. The theory and geometry of the sonic anemometer employed in this study in relation to the potential cause of this error are reviewed and we present evidence supporting this theory. In addition, a further refinement of the sound path error is included which accounts for asynchronous sound pulse sampling. A suggested correction is applied to experimental data and its effect on resulting fluxes are analysed.

H.3 Materials and methods

Field measurements of sensible heat fluxes and supporting variables were collected at the Griffin EUROFLUX experiment site, latitude 56° 36’30”N, longitude 3° 47’ 15”W. The site vegetation is a monoculture of Sitka Spruce ($Picea sitchensis$) that was planted in 1980-1981. The canopy height at the time of measurement was approximately 7 m, with a LAI of about 8. Data for this analysis were taken from the year 1998.
The eddy covariance instrumentation and processing methods follow the specifications laid out in Aubinet et al. (2000). Wind velocity components and the sonic temperature signals used in this experiment were measured using a Gill Solent 101R2 sonic anemometer, as part of a flux measurement system (Moncrieff et al., 1997). The anemometer was mounted at the top of a tri-pole tower at a height of 15.5 m. Coincident fast-response temperature measurements were obtained from a fine wire thermocouple (Krovetz et al., 1988) mounted with a 30 cm separation from the centre of the sonic anemometer. The thermocouple wire had a diameter of 0.004 cm, which lasted from hours to weeks depending upon environmental conditions. Thermocouple data were digitised using analogue input channels of the sonic anemometer. Raw data signals were collected at 20.833 Hz and stored on CD for further analysis.

Post processing of the data was carried out using the EdiRe software package developed by the author. In post processing, velocity signals were rotated using methods described by McMillen (1998), but no filtering or detrending of the data was performed. Potential errors due to sensor separation were minimised by removing any time lag between the thermocouple temperature and vertical velocity signal. Sonic temperatures were corrected as specified in the text. For the energy budget comparison, net radiation, soil heat flux and latent heat flux measurements were adjusted for sensor calibration. The soil heat flux was corrected for storage in the overlying soil layer following the method of Mayocchi and Bristow (1995) while latent heat fluxes were adjusted for canopy storage using within canopy profile measurements of humidity. Frequency response corrections were applied to the latent heat fluxes following the methods of Moore (1986) but were not applied to the sensible heat fluxes.

H.4 Theory

H.4.1 Definition of equation

The theory of measurement of air temperature using speed of sound as measured by a sonic anemometer have been well described (Kaimal and
One finer detail that has not been considered in treatment of this subject is the potential for errors in the variables describing sonic temperature. In the following section we will follow the development of this theory, but we will include error terms for variables previously assumed constant. We develop the equations which describe the relation between true temperature and sonic temperature and a corresponding equation describing sensible heat flux. We then develop the theory to define and ascertain the indeterminate path length variable.

Air temperature, $T$, may be measured using the speed of sound, $c$, in a gas of constant density, as in equation (1). The speed of sound may be determined from the travel times, $t_1$ and $t_2$, of sound pulses travelling in opposite directions along a path length, $L$, equation (2). The values of $t_1$ and $t_2$ are obtained from sonic anemometer measurements. If any of the variables involved in this calculation change, errors will be introduced into the sonic measurement of the speed of sound, and hence temperature.

$$T = \frac{c^2}{403}$$  \hspace{1cm} (1)

$$c = \frac{L}{2 \left( \frac{1}{t_1} + \frac{1}{t_2} \right)}$$  \hspace{1cm} (2)

Following Kaimal & Gaynor (1991), and using the modified sound vector field as shown in figure 1, the sound pulse transit times may be described as:

$$\frac{1}{t_1} = \frac{c \cdot \cos(\gamma_1) + V_d}{L_m}$$

$$\frac{1}{t_2} = \frac{c \cdot \cos(\gamma_2) - (V_d + \Delta V_d)}{L_m}$$  \hspace{1cm} (3)

where

$$\gamma_1 = \sin^{-1} \left( \frac{V_u}{c} \right)$$

$$\gamma_2 = \sin^{-1} \left( \frac{V_u + \Delta V_u}{c} \right)$$  \hspace{1cm} (4)
These equations differ from those given by Kaimal & Gaynor (1991) by the replacement of the expected path length with the value of the path length at the time of measurement ($L_m$) and the inclusion of the change in velocity along the sound path $\Delta V_d$ and normal to the sound path $\Delta V_n$ as given in the descriptions of $t_2$ and $\gamma_2$.

In previous theoretical developments, the path length, $L$, has been assumed constant. With this value held constant, the speed of sound from equation (2) may be affected by the path length at the time of measurement ($L_m$) implicit in the transit times, equation (3). Here we have assumed that the value of $L_m$ is constant over the period required to measure the two transit times $t_1$ and $t_2$.

Previous theoretical developments have also not included the effect of flow acceleration, which appears in the equations for $t_2$ and $\gamma_2$. In still air the values of $t_1$ and $t_2$ will be identical. Similarly, for air at constant velocity, the values of $t_1$ and $t_2$ will average to their equivalent value for still air of the same temperature. However, for a parcel of air which is accelerating along the measurement path there will be an increase or decrease in the transit time $t_2$ which is not related to air temperature but is instead directly related to the change in velocity between the times of measurement of $t_1$ and $t_2$ resulting from the presence of $\Delta V_d$ and $\Delta V_n$.

Following Kaimal & Gaynor (1991) and including terms for flow acceleration over the measurement period, the speed of sound as measured by a sonic anemometer, $c_a$, may be written:

$$c_a = \frac{L}{2} \left[ \frac{c \cdot \cos(\gamma_1) + V_d}{L_m} + \frac{c \cdot \cos(\gamma_2) - (V_d + \Delta V_d)}{L_m} \right] \quad (5)$$

Substituting for the definition of $\gamma$ from equations (4) and combining terms gives:

$$c_a = \frac{1}{2} \cdot \frac{L}{L_m} \left[ \left( c^2 - V_n^2 \right)^{1/2} + \left( c^2 - V_n^2 - 2 \cdot V_n \cdot \Delta V_n - \Delta V_n^2 \right)^{1/2} - \Delta V_d \right] \quad (6)$$

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Performing a binomial series expansion of the second term within the square brackets and retaining only the first two terms of that expansion but excluding terms which contain a squared velocity change, and then carrying through with the multiplication of 1/2, gives us an equation describing the speed of sound as measured by a sonic anemometer:

\[
c_a = \frac{L}{L_m} \left[ \left( c^2 - V_n^2 \right)^{\frac{3}{2}} - \frac{V_n \cdot \Delta V_n}{2 \cdot \left( c^2 - V_n^2 \right)^{\frac{1}{2}}} - \frac{\Delta V_d}{2} \right]
\]  

(7)

The desired value from this equation is the speed of sound, \( c \), and the other variables must be determined in order to ascertain its value. The value of \( L \) in this equation is implicit in the manufacturers signal processing and is given in the sensors documentation, while the values of \( c_a, V_n, \Delta V_d, \) and \( \Delta V_n \) are available from the anemometers output. The value of \( L_m \) is unknown, and will be discussed in the following section.

A typical value of the change in velocity between samples is on the order of 0.1 m s\(^{-1}\). For the anemometer used in this experiment, eight sets of six transit times are measured for each sample output, giving a change in velocity between \( t_1 \) and \( t_2 \) which is on the order of 0.021 times the change in velocity between samples. While the values of \( \Delta V_n \) are of the same magnitude as those of \( \Delta V_d \), the large denominator in the second term within the brackets suggests that this term will be about two orders of magnitude smaller than the third term, and may reasonably be ignored, giving:

\[
c_a = \frac{L}{L_m} \left[ \left( c^2 - V_n^2 \right)^{\frac{3}{2}} - \frac{\Delta V_d}{2} \right]
\]  

(8)

Employing equations (1) and (8), we may define the temperature as measured by the sonic anemometer:
Expanding the numerator we eliminated the squared velocity difference term as being negligibly small. After rearranging, with the use of equation (1), we may then define the sonic temperature in terms of true temperature instead of speed of sound:

\[
T_s = \left( \frac{L}{L_m} \right)^2 \left[ T - \frac{V_n^2}{403} - \frac{\Delta V_d}{20.07} \right]^{\frac{1}{2}}
\]  

(10)

In so doing, we have approximated the value of \(T\) in the last term using the value of \(T_s\). This may be rearranged to describe the actual temperature in terms of \(T_s\).

\[
T = \left( \frac{L_m}{L} \right)^2 T_s + \frac{V_n^2}{403} + \frac{\Delta V_d}{20.07} T_s^{\frac{1}{2}}
\]  

(11)

The final addition is to include the correction for the effect of changes in density due to constituent changes, primarily water vapour, as has been described by Schotanus et. al. (1983) and Kaimal & Gaynor (1991). If uncorrected for water vapour, the resulting temperature is nearly equivalent to the virtual air temperature, and may be used in this form for the calculation of stability terms, which require the use of virtual temperature.

\[
T = \left( \frac{L_m}{L} \right)^2 T_s + \frac{V_n^2}{403} + \frac{\Delta V_d}{20.07} \frac{T_s^{\frac{1}{2}}}{20.07} - 0.00032 \cdot \bar{T} \cdot q
\]  

(12)

In order to couch the equation in flux terms, we separate the variables into their mean and deviation components. The mean \(w\) and mean \(\Delta V_d\) have been excluded, as their values are assumed equal to zero. Expanding equation (12) and Reynolds averaging results in the flux equation, of which we have only retained the higher order products of the second term:
This formulation is similar to that given by Schotanus et al. (1983) and Kaimal & Gaynor (1991) with the exception of the retention of the 4th term, the addition of the 2nd and 5th terms, and the modifiers for path length differences in the first term. All the terms of equations (12) and (13) are measurable with the exception of the variables including $L_m$. Therefore, we next define the relationship of the variable $L_m$ to horizontal wind speed and direction, for the anemometer under consideration.

H.4.2 Geometry of velocity dependent path length changes

The geometry of the distortion of a sonic anemometer’s sensor probe will determine the value of $L_m$, resulting in confounding effects of sonic temperature measurement. As this effect is inherently sensor dependent, the resulting equations will apply specifically to the anemometer used in its derivation, in this analysis the Gill Solent 101R2. Some assumptions are also required to allow us to simplify the theory involved. We have assumed that any flow distortion resulting from probe design has been fully compensated by the manufacturer’s correction matrix. Grelle & Lindroth (1994) have discussed this topic and the weaknesses of this assumption will not be addressed further within this paper. More specific to this anemometer, we have assumed initially that the horizontal (aluminum) structure elements are inelastic relative to the vertical (carbon fibre) structure supports. We have assumed that the deformation of the sensor head is uniform for azimuthal changes in forcing and that there are no torsional forces acting on the sensor head. We assume the transducer support arms are inelastic and that the vertical structure support deformation acts such that the vertical supports are inelastic but the connections between the vertical supports and the horizontal supports are elastic. An alteration of this last assumption so that the vertical supports were considered elastic and deform in a sinusoidal manner showed insignificant
effects on the final results. Some values that we have assumed in these calculations include: the drag coefficient of the sensor head \((Cd = 2)\), the area of drag of the sensor head \((Area = 18 \text{ cm}^2)\), and the sonic's path length under calm conditions \((L = 15 \text{ cm})\).

Figure 2 shows the geometry describing the path between two transducers mounted at the end of support arms. The support arms are mounted with a separation, \(R (0.165 \text{ m})\). Each transducer support arm displaces its transducer, in opposing directions, from the sensors vertical axis, \(R\), by a distance \(X (0.0530 \text{ m})\) along the \(x\)-axis. Each support arm displaces its transducer vertically towards the centre of the probe, parallel to the \(z\) axis, by an amount \(Z (0.0295 \text{ m})\). Note that in figure 2, the bottom transducer is located at the origin so that the displacement of the upper transducer incorporates the displacements of both upper and lower transducer support arms. The resulting separation between the transducers, \(L_m\), is the path over which the sonic temperature is measured.

An ideal supporting structure would be rigid so that the path length \(L_m\) would be unresponsive to wind forces. Flexibility in the vertical support structure results in a displacement of the upper transducer arm by an angle \(\omega\) for wind from the direction \(\theta\). The anemometer employed in this analysis measures temperature using the transducer pair which lies along the axis defining the \(u\) wind component (the \(x\) axis in Figure 2 ). Therefore wind velocity and direction are calculated from the anemometer's unrotated horizontal wind components \(u\) and \(v\) as:

\[
V = \sqrt{u^2 + v^2} \tag{14}
\]

\[
\theta = \tan^{-1}\left(\frac{v}{u}\right) \tag{15}
\]

The angle \(\omega\) with which the upper transducer arm is displaced by a wind of given velocity can be estimated using a modification of the equation describing
the force applied to the anemometers upper transducer arm support structure (Welty et al., 1984):

$$\omega = Da \cdot Area \cdot Cd \cdot \frac{\rho}{2} \cdot V^2$$

(16)

in which \(Area\) \((m^2)\) is area of horizontally projected area of the upper half of the sonic probe, \(Cd\) is the drag coefficient, \(\rho\) is the density of air \((kg \cdot m^{-3})\) and \(V\) is the wind speed \((m \cdot s^{-1})\). The standard equation describing the force of a fluid has then been altered by including a wind force dependent displacement angle \(Da\) \((deg \cdot s \cdot kg^{-1} \cdot m^{-1})\), which determines the head displacement for a given wind force. If we determine the displacement angle associated with a given wind velocity, we may then describe the effective path length over which a corresponding sonic temperature measurement is made:

$$L_m = \sqrt{\left(R \cdot \cos(\theta) \cdot \sin(\alpha) + 2 \cdot X\right)^2 + \left(R \cdot \sin(\theta) \cdot \sin(\alpha)\right)^2 + \left(R \cdot \cos(\alpha) - 2 \cdot Z\right)^2}$$

(17)

**H.4.3 Method of estimating the velocity dependent displacement angle**

From equation (9) defining the temperature as measured by the sonic anemometer, we know that the only missing variable required to define the effect of distortion of probe head is the measurement path length \(L_m\). Equation (17) describes \(L_m\) in relation to wind direction and wind speed, but leaves us with an alternate missing variable, the velocity dependent displacement angle, \(\omega\). Other empirical solutions to this problem exist, \(i.e.\) direct measurements of the effects of applied forces, and wind tunnel studies under controlled temperature conditions) and could be used to determine the desired displacement angle velocity relationship. However we have attempted an *in situ* approach of comparing the sonic temperature with that measured by a fine wire thermocouple as it is an approach that could easily be replicated by other researchers.
This approach, requires us to know the error term for the thermocouple temperature. We assume that the fine wire thermocouple temperature, $T_c$, is responding linearly to true temperature, $T$, but has an offset from true temperature, $\Delta T_c$. The relationship between true temperature and thermocouple temperature may then be defined as:

$$T = T_c + \Delta T_c$$  \hspace{1cm} (18)

Assuming that under calm conditions $L = L_m$, the sonic temperature will represent the true temperature when adjusted for humidity. Equations (12) and (18) may then be combined and rearranged to provide an estimate of $\Delta T_c$:

$$\Delta T_c = \left( \frac{T_s}{1 + 0.00032 \cdot q} \right) - T_c$$  \hspace{1cm} (19)

This estimate of $\Delta T_c$ is then used to define the path length at the time of measurement:

$$L_m = L \cdot \sqrt{\left( \frac{(T_c + \Delta T_c) - \frac{V_s^2}{403} - \frac{\Delta V_d \cdot (T_c + \Delta T_c)^{3/2}}{20.07} + 0.00032 \cdot (T_c + \Delta T_c) \cdot q}{T_s} \right)}$$  \hspace{1cm} (20)

We must assume that the thermocouple error term is reasonably constant in time and that it is not a function of either wind speed or humidity. This will not be entirely true, as thermal loading of the thermocouple will make it sensitive to fluctuations in low wind speed on sunny days. However, we evaluate $L_m$ for high wind speed conditions to minimize this problem.
H.5 Results

H.5.1 Determination of $\omega$ and $L_m$

We employed equation (20) to calculate the instantaneous values of $L_m$. These values were averaged by classes of wind direction and wind speed. For this analysis wind directions are specified relative to the path of the sonic temperature measurement, e.g. 0 degrees is for wind coming from the positive x axis and +90 degrees is for wind coming from the positive y axis in Figure 2. In Figure 3, we present these data for wind directions of 0 (+/- 10) and 180 (+/- 10) degrees. Consistent with theory, in this figure we observe a shortening of the sonic path for winds coming from the direction of the upper sonic transducer (0 degrees). A smaller lengthening of the path is observed for winds coming from the opposing direction. We would expect an equal and opposing effect on path length for winds from these opposing directions; the lack of such a response is unexplained. Nevertheless, we are still able to estimate the value of $Da$ from the difference in the responses for the two wind directions at high wind speeds. Using equation (17) and evaluating it for winds from 0 and 180 degrees relative to the sonic’s path, we can describe the differences in path lengths as:

$$L_{m_0}^2 - L_{m_0}^2 = -8 \cdot R \cdot X \cdot \sin(\omega)$$

From Figure 3, the difference between the 0 and 180 degree averaged path lengths at a velocity of 12 m s$^{-1}$ is approximately 0.6 mm which, because we are looking at opposing wind directions, should be twice the displacement for each of the two wind directions individually. From this displacement we calculated a value for $Da$ of 0.28 deg s kg$^{-1}$ m$^{-1}$. This value was used as an initial estimate in determining a function to accurately define values of $Da$ for use in equation (16). From Figure 3 we also inferred that the response of $Da$ to wind direction may not be uniform as assumed. We therefore reprocessed a subset of the sonic temperature data employing a range of constant values of $Da$. The heat flux error term (corrected $H_s - H_{tc}$) was grouped by wind speed and wind direction to give a rough directional response of $Da$. These results
were then fit with a sinusoidal model of $Da$ to take into account directional responses of $Da$:

$$Da = a + b \cdot \sin(c \cdot \theta + d) + e \cdot \sin(f \cdot \theta + g)$$  \hspace{1cm} (22)

The model correction was applied to one month’s data, and the differences between the model corrected $H_s$ and $H_{tc}$ were examined. This process was repeated numerous times and the residual error analysed with respect to wind direction until an apparently optimal form of equation (22) was determined. We observed that the sinusoidal model of $Da$ was better than any constant value of $Da$. However, wind tunnel tests may be needed to establish an ideal form and coefficients for equation (22). The resulting form for equation (22) was:

$$Da = -0.5 - 0.5 \cdot \sin((\theta + 110) \cdot 0.8) - 0.02 \cdot \sin((\theta + 135) \cdot 2)$$  \hspace{1cm} (23)

Because these coefficients were determined for a data subset, we verified the effect of the sine function described in equation (23) by correcting the remainder of the years data. The results of this analysis are shown in following sections.

### H.5.2 Proportional effects of sonic temperature correction for distortion and flow acceleration

The correction proposed in equation (12) incorporates the effects of two components. The proportional effects of those two components are described in Table 1. The data used in determining the component effects was the same as that used in determining the final correction effects. Table 1 gives the average, standard deviation, minimum and maximum values for the corrections to $H_s$ as proposed by Schotanus et. al. (1983) and as proposed in this paper. The combined effect of the individual acceleration and deformation corrections are given as well as the correction combining all terms.
The correction component values in Table 1 indicate that the corrections for acceleration and deformation are of the same order of magnitude as the standard corrections described by Schotanus et. al. (1983). For the data set to which these corrections were applied, the acceleration term had a net negative effect and the deformation had a net positive effect. Both the acceleration and deformation terms may be affected by the orientation of the sonic head with respect to the mean flow so that the average corrections stated here are not necessarily indicative of these corrections applied under different experimental conditions. It is quite plausible that for different wind conditions the net effect of these components could be negative, positive or zero. In this situation, however, the two additional correction components proposed are of opposing sign and result in a small positive adjustment in the net correction as compared to the standard correction.

**H.5.3 Expected effects of revised sonic temperature correction**

From equation (12) we know that sonic temperature will be less than the true temperature for higher wind velocities. Alternately, at higher humidity sonic temperature will be higher than true temperature. It has already been shown (Kaimal and Gaynor, 1991) and (Hignett, 1992) that correction for these effects typically results in a negative offset to H. Based on the theory derived above, increases in measurement path length and flow acceleration will both cause sonic temperature to be less than true temperature.

More precisely, from equation (17), we know that the sonic temperature measurement path length will increase for winds from around 0 degrees and decrease for winds from around 180 degrees. For strong correlations between \( w \) and \( u \), the measurement path length \( L_m \) will be correlated with \( w \) because of the velocity terms in equation (16). As a result, variations in \( L_m \) should cause a positive heat flux error for winds from relative north and a negative error for winds from relative south. We do not have predefined expectation of the effect of the acceleration terms. It will obviously be a function of the correlation of
the characteristics of the along path flow with those of wind direction and vertical velocity.

The effect of the proposed additional corrections on sonic temperature statistics will be small relative to the effect on fluxes because the coherence between T and the controlling wind velocity variables is smaller than that for w and these variables. Indeed the observed effect of these corrections on sonic temperature means and standard deviations was on the order of 1% or less. Therefore the effect of the proposed correction on temperature statistics is not considered further. However, because of the autocorrelation between the variables controlling the magnitude of the proposed correction and the vertical velocity incorporated in the sensible heat flux, the potential effect of the proposed correction upon sensible heat flux is greater. In this paper we have assumed that the effect of noise on the correction terms is small in comparison to the natural correction term.

H.5.4 Observations on the effects of revised sonic temperature correction

The sample time series given in Figure 4, compares corrected and uncorrected forms of $H_s$ with $H_{tc}$ and a corresponding trace of wind speed. We observe a close relationship between $H_{tc}$ and uncorrected $H_s$. However, after the standard correction is applied, $H_s$ is much lower than $H_{tc}$. After correction for the model proposed, equation (12), there is better correspondence, at higher wind speeds, between the sensible heat flux measured with the two different temperature sensors.

In Figure 5 the difference between $H_{tc}$ and the various forms of $H_s$ are compared as a function of wind speed for eight wind direction categories. We observe that for winds from +/-90 to +/-180 (i.e. the top four panels in Figure 5) the uncorrected $H_s$ (unmarked line) exceeds $H_{tc}$ by about 10 W m$^{-2}$ for wind speeds near 5 m s$^{-1}$, as can be expected from equation (17). Similarly, for winds from 0 to +/-90 degrees (bottom four panels in Figure 5) and at wind
speeds near 5 m s\(^{-1}\), we observe an equivalent or slightly larger decrease of about -25 W m\(^{-2}\) in \(H_s\) as compared to \(H_{tc}\). This is roughly in agreement with our previous determination of \(L_m\) which suggested an error which was greater for a wind regime near 0 degrees.

From Figure 5 we also observe that the standard sonic temperature correction is wind direction independent. With this correction applied (open circles), \(H_s\) is more negative than the uncorrected sensible heat flux, by an approximately similar magnitude for all wind directions. The dependence of this correction on wind speed reflects the greater turbulent transport of latent heat and momentum at higher wind speeds, equation (13).

In contrast to the standard correction, we observe in Figure 5 that the model correction does exhibit a wind direction dependence, as is implied by equation (17). The proposed correction is positive for winds from +/-90 to +/-180 and negative for winds from 0 to +/-90 degrees. For all wind direction categories, except -135 to -90 degrees, the proposed correction improves the correspondence of \(H_s\) with \(H_{tc}\). We observe that the model correction does not give a perfect fit to \(H_{tc}\). This suggests that further work is needed in refining the model describing \(Da\), or determining other errors in the measurement of sonic temperature.

If we compare the results as shown in Figure 5 with those presented by Grelle and Lindroth (1996), we observe greater error in \(H_s\) at lower wind speeds. Their data indicate that the effect of sonic deformation is not notable until wind velocities on the order of 8 to 10 m s\(^{-1}\) are reached. Our analysis, however, indicates noticeable effects for wind velocities as low as 3 m s\(^{-1}\). This discrepancy likely arises from combining data when presenting their results, as merging the data from opposing wind directions would have the effect of combining errors of different signs, resulting in a small net error. Because, their data set has fewer data at higher wind speeds, it is possible that these data come from an unequal distribution of wind directions, and hence a more obvious distortion error effect.
To examine the net effect of the corrections being investigated we present the results for sensible heat fluxes from 1998 as cumulative differences ($\Sigma (H_{tc} - H_s)$) and cumulative absolute differences ($\Sigma |H_{tc} - H_s|$). These differences portray a visual representation of the accuracy and precision of the associated correction changes with time. These results are presented in Figure 6 and Figure 7, in which Figure 6a and Figure 7a illustrate results used for the development of the model $Da$, equation (23), while Figure 6b and Figure 7b contain results for the final model of $Da$ applied to the remainder of the years data. The data in these figures are plotted against consecutive runs instead of date/time in order to avoid the gaps in the time series caused by missing data.

The cumulative differences shown in Figure 6a and b provide a visual estimate of the accuracy of the various forms of $H_s$ in representing $H_{tc}$. In the development data of Figure 6a, the net accuracy indicates that uncorrected $H_s$ overestimate $H_{tc}$. However, the net accuracy is quite good for the verification data in Figure 6b (i.e. the end point of the uncorrected $H$ difference is quite close to zero). In both the development and verification data the standard correction applies a consistent negative offset, resulting in a $H_s$ that is consistently smaller than $H_{tc}$.

In Figure 6a, an example of the proposed correction with a constant value for $Da$ (-0.28 in this case) is presented to show how the correction responds to constant values. For this data set the constant value of $Da$ resulted in a net negative offset, causing the model to underestimate $H_{tc}$ even more than the standard correction. The model $Da$ applied to the development data produced a good agreement, however, when applied to the verification data, the correction using model $Da$ resulted in a $H_s$ that was more positive than the standard corrected $H_s$ but still considerably underestimated $H_{tc}$. It is possible that the choice of data used in developing the model values of $Da$ were in some way unrepresentative of the verification data. While some inaccuracy may stem from an innate inability to obtain a “true” model to define $Da$ under all circumstances, selection of a more representative data set when developing a model for $Da$ may result in a more accurate correction. We must also consider
the possibility that slight calibration inaccuracies in the thermocouple temperature sensor result in a net bias in the comparison of accuracy by this method.

The cumulative absolute differences between $H_{\text{tc}}$ and $H_s$ shown in Figure 7a and b, provide a visual comparison of the precision of the various forms of $H_s$ in representing $H_{\text{tc}}$. For the development data, Figure 7a, the effect of the standard correction was ambiguous. The standard correction exhibited periods of improved and worsened precision of the $H_s$ in comparison with $H_{\text{tc}}$. In the verification data, Figure 7b, the effect is more consistent in that the standard correction exhibits consistently lower precision, (i.e. greater cumulative absolute error), as compared to the uncorrected $H_s$. For the development data we again note that the modelled $Da$ values show considerable improvement over the use of a constant value of $Da$. When applied to the verification data the modelled $Da$ values exhibit an improvement in the precision as compared to the standard correction. The improvement in precision of the proposed correction is still less than the precision of the uncorrected $H_s$. Further refinement of the model describing $Da$ could improve upon the precision with which the corrected $H_s$ represents a true sensible heat flux.

When the corrected $H_s$ is incorporated into an energy budget comparison, Figure 8, we observe a 2% increase in the $H+LE$ term as a result of incorporation of the proposed correction. This increase is consistent with the proposed correction being 2.5 W m$^{-2}$ greater than standard corrections, as shown in Table 1.

### H.6 Conclusions

Fluxes of sensible heat determined from measurements of sonic anemometer speed of sound derived temperature are known to have errors caused by cross wind velocity and humidity fluctuations. The corrections for these errors are well known and are applied as standard practise to sonic temperature derived sensible heat fluxes Aubinet et al. (2000). The observation by other researchers
(Grelle and Lindroth, 1996) that an additional error exists as a result of sonic probe deformation is supported by the observations of the authors. We have developed a theory to further correct sonic temperature measurements based on the geometry of the anemometer employed in the analysis. In deriving this theory we have also incorporated a term approximating the effect of flow acceleration. Because it depends only on the determination of the acceleration of velocity signals along the path of sonic temperature measurement, the correction component for acceleration may be easily incorporated into the correction of sonic determined air temperature measurement. The correction for probe distortion, on the other hand, requires accurate supporting measurements of air temperature and empirical determination of a deformation coefficient \( Da \) relevant to the anemometer being corrected. While a procedure is described for the anemometer used in this experiment, the resulting theory may not apply directly to other models of sonic anemometer. We have estimated corrections for probe distortion and flow acceleration that are of the same order of magnitude as the standard corrections of Schotanus et. al. (1983). The distortion component of this correction had an average effect of +7.5 W m\(^{-2}\) and the acceleration component had an average effect of -4.8 W m\(^{-2}\). The corresponding net effect of the proposed corrections increase the average flux by approximately 2.5 W m\(^{-2}\), which corresponds to an improvement in energy budget closure of 2\% for the data presented. As the proposed correction is both wind velocity and wind direction dependent the observed improvement can not be assumed for application of this correction to other experimental data. The effect of this correction will be determined by the anemometer's construction, sampling frequency, and site wind characteristics. It may be beneficial to further determine the extent to which this deformation effect is applicable to and consistent with other sonic probes.
Table 1. Values of average, standard deviation, maximum, and minimum of the standard correction, components of the proposed correction model, and the proposed correction model.

<table>
<thead>
<tr>
<th>Method</th>
<th>Average</th>
<th>Std dev</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>-7.3</td>
<td>13.9</td>
<td>-141.0</td>
<td>109.5</td>
</tr>
<tr>
<td>Model acceleration</td>
<td>-4.8</td>
<td>15.6</td>
<td>-190.0</td>
<td>84.3</td>
</tr>
<tr>
<td>Model deformation</td>
<td>7.5</td>
<td>19.2</td>
<td>-85.0</td>
<td>200.2</td>
</tr>
<tr>
<td>Model (standard + acc + def)</td>
<td>-4.6</td>
<td>13.7</td>
<td>-141.5</td>
<td>109.5</td>
</tr>
</tbody>
</table>
Figure 1. Schematic representation of sonic anemometer sound path vector travel. Schematic representation including effects of cross-path velocity component and asynchronous sampling of sound path travel times.

Figure 2. Schematic diagram demonstrating the sonic anemometer head deformation geometry. The heavy line \((L_m)\) represents the sonic sensing path with the heavy dots at each end representing a sonic transducer. Note that the sonic transducer positions have been shifted so that the bottom transducer is located at the origin. The relevant deformation angle is \(\omega\) and \(\theta\) is the wind direction.

Figure 3. Averaged instantaneous estimations of measurement path length grouped by wind velocities from 0 to 12 m s\(^{-1}\), for two opposing wind directions.

Figure 4. Sample time trace exemplifying the differences between sensible heat fluxes measured with sonic and thermocouple temperature. Standard and model corrections to sonic sensible heat flux are also shown, as is the corresponding horizontal wind speed.

Figure 5. Sensible heat flux difference (sonic – thermocouple) vs wind speed for different wind directions relative to the path of the sonic temperature.

Figure 6. The cumulative difference between forms of sonic sensible heat flux and thermocouple sensible heat flux: a) results for model development, b) results for the model applied to the remainder of the years data.

Figure 7. The cumulative absolute difference between forms of sonic sensible heat flux and thermocouple sensible heat flux. a) results for model development, b) results for the model applied to the remainder of the years data.
Figure 8. Energy budgets comparison using sensible heat flux determined from sonic temperatures, with standard (dark circles) and model corrections (open circles) applied.
Figure 1
Figure 2
Figure 3

- Instantaneous wind velocity (m s\(^{-1}\))
- Measurement path, \(L_m\) (m)

- 0 +/- 10 deg
- 180 +/- 10 deg
- 0 deg fit
- 180 deg fit
Figure 4
Figure 5
Figure 6
Figure 7

(a) Cumulative absolute difference (W m\(^{-2}\)) vs. Run

(b) Cumulative absolute difference (W m\(^{-2}\)) vs. Run

Legend:
- Sonic - Thermocouple
- Standard correction - Thermocouple
- Model - Thermocouple
- Constant Da (-0.28) - Thermocouple
\[ (\text{LE} + H \text{ (standard correction)}) = 0.6705 \times (Rn-G) - 14.234 \]
\[ R^2 = 0.912 \]

\[ (\text{LE} + H \text{ (model)}) = 0.6565 \times (Rn-G) - 15.794 \]
\[ R^2 = 0.9133 \]

Figure 8