Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy.

SRNL-STI-2008-00463

Accurate temperature measurements in naturally-aspirated radiation shields

Robert Kurzeja Aug 20, 2009 16:30
Savannah River National Laboratory

Abstract

Experiments and calculations were conducted with a 0.13 mm fine wire thermocouple within a naturally-aspirated Gill radiation shield to assess and improve the accuracy of air temperature measurements without the use of mechanical aspiration, wind speed or radiation measurements. It was found that this thermocouple measured the air temperature with root-mean-square errors of 0.35 K within the Gill shield without correction.

A linear temperature correction was evaluated based on the difference between the interior plate and thermocouple temperatures. This correction was found to be relatively insensitive to shield design and yielded an error of 0.16 K for combined day and night observations.

The correction was reliable in the daytime when the wind speed usually exceeds 1 m s^{-1} but occasionally performed poorly at night during very light winds. Inspection of the standard deviation in the thermocouple wire temperature identified these periods but did not unambiguously locate the most serious events. However, estimates of sensor accuracy during these periods is complicated by the much larger sampling volume of the mechanically-aspirated sensor compared with the naturally-aspirated sensor and the presence of significant near surface temperature gradients. The root-mean-square errors therefore are upper limits to the aspiration error since they include intrinsic sensor differences and intermittent volume sampling differences.

1. Introduction

Although it is generally recognized that accurate air temperature measurements require mechanical aspiration, natural aspiration is nevertheless of interest in boundary layer meteorology because many sites, for example, ocean buoys, do not have sufficient electrical power for extended fan operation. However, the cost and physical size of aspirators are also limitations.

Recent studies have discussed the accuracy of naturally-aspirated temperature sensors (Erell et al., 2005, Nakamura and Mahrt, 2005). These studies have investigated the radiation protection and ventilation properties of various shields and also methods for estimating the temperature error from concurrent radiation and wind speed measurements.

However temperature error correction based on wind and radiation measurements is not always possible because of significant variability over short distances (10 metres). This is the case in forest canopies or in urban environments. Thus, there is a need for small, low power, self-contained sensors that can measure the temperature to 0.1 K accuracy for a range of radiation loading without the need for supplementary measurements.

Previous studies, e.g. Erell et al. (2005), Richardson et al. (1999), have recognized that temperature accuracy improves with decrease in sensor size because the convective heat exchange efficiency improves. This suggests the use of a temperature sensor small enough to maximize ventilation efficiency but durable enough to withstand weather extremes.

This paper discusses the performance of a fine wire thermocouple (0.13 mm diameter) within a standard Gill radiation shield. This size thermocouple was found to be large enough for easy fabrication but durable enough for months of service. The Gill radiation shield is widely used and has been studied extensively.

The sensor's error within and outside of the Gill shield is modeled and then it is shown that an error of less than 0.1 K is not possible without a correction for the shield temperature. Fine wire thermocouple and shield measurements are compared with concurrent measurements of solar and infrared radiation, and wind speed for a 7-day period in April/May. The performance of the thermocouple was compared with a comparable sensor within a mechanically-aspirated enclosure.

A linear parameterization of the sensor error in terms of the difference between the shield plate temperature and the fine wire temperature is evaluated for a range of wind speeds and thermal loading.

2. Design considerations

It is well known that small sensors are less affected by solar and infrared radiation than larger ones because of more effective heat exchange with the atmosphere, e.g., Fritschen and Gay (1979). In fact, ultra fine wire (<0.01 mm) sensors can be used without any shielding but are not durable enough for extended exposure to the elements. Thus, a starting point for accurate naturally-aspirated temperature measurement is the use of the smallest possible sensor.

The most common sensors employed in field measurements are platinum resistance sensors and thermistors. Thermocouples are used less often because they require a separate reference temperature and accurate voltage measurement. However, their advantages include a broad range of sizes, low cost and high relative accuracy for measuring temperature gradients. This paper focuses on measurements with thermocouples but the results can be extended to other sensors of comparable size.
The first step in the assessment of thermocouple error is to estimate thermocouple performance as a function of wire size. The temperature measurement error is derived

from a balance between (1) convective heat exchange with ambient air, (2) exchange of infrared radiation with the temperature shield, and (3) absorption of solar radiation by the sensor.

The beneficial effect of small size on sensor sensor accuracy with reduced aspiration can be seen from the discussion in Fritschen and Gay (1979), Section 3.2. They expressed a sensor's time constant, τ, as,

$$\tau = \rho C V / h A \quad (1)$$

where,

ρ = density (kg m^{-3})
C = heat capacity (J kg^{-1} K^{-1})
V = volume (m^3)
h = heat transfer coefficient (J m^{-2} s^{-1} K^{-1})
A = sensor area (m^2)

The heat transfer coefficient can be expressed as,

$$h = Nu\, k / d \quad (2)$$

where,

Nu = Nusselt number
k = thermal conductivity of air (J m^{-1} s^{-1})
d = sensor diameter (m)

A common expression for a sensor's temperature change with time is,

$$dT_s/dt = -(T_s - T_a) / \tau \quad (3)$$

where,

T_s = sensor temperature (K)
T_a = ambient air temperature (K)
τ = sensor time constant (s)

The sensor solar radiative heating rate Q_s (K s^{-1}) for diffuse radiation is given by,

$$Q_s = a R A / (\rho C V) \quad (4)$$

Where,

a = solar absorptivity
R = solar radiation (J m^{-2} s^{-1}).

For steady state conditions Eqs. (1) – (4) combine to give,

$dT_s/dt = 0 = -(T_s - T_a) / \tau + a\,R\,A/(\rho CV)$

or,

$$T_s - T_a = aR/h \qquad (5)$$

Since the heat transfer coefficient is inversely dependent on the sensor diameter, the aspiration error, $(T_s\text{-}T_a)$, will increase with sensor size.

Fritschen and Gay point out other effects of the sensor time constant, e.g., temperature lag and attenuation of high frequencies. However, these effects will only be important for sampling periods comparable to or less than the sensor time constant and will not affect the accuracy of longer time averages. Thus, a 1 minute time constant - typical of many temperature sensors - will be a source of error in a 1-minute average but not in a 15-minute average, except possibly during a rapid change in temperature. Since this study employs fine wire thermocouples with time constants of 1-10 seconds, no impact on a 5-minute average is expected.

A simple calculation illustrates the effect of wire size on temperature error for thermocouple wires outside and within a radiation shield. First, consider a situation when significant heat loading occurs, e.g., in clear skies, a 45 degree solar zenith angle, an ambient wind speed of 1 m s^{-1}, and solar isolation of 700 W m^{-2}.

The temperature of an exposed thermocouple wire can be calculated with the hot-wire transfer equation discussed by Friehe (1986). The convective heat loss from a wire is given by,

$$Q_c = h_w(T_a - T_w) \qquad (5)$$

where,

- Q_c = convective heat transfer to the air (J m^{-2} s^{-1})
- h_w = wire heat transfer coefficient (J m^{-2} s^{-1} K^{-1})
- T_a , T_w = ambient air and wire temperatures (K)

The wire heat transfer coefficient is given by,

$$h_w = Nu\; k / d_w \qquad (6)$$

- k = thermal conductivity of air (J m^{-1} s^{-1})
- d_w = wire diameter (m)

Friehe recommended an expression for the wire Nusselt number given by Collis and Williams (1959).

$$Nu = 0.24 + 0.56Re^{0.45} \qquad Re < 44 \qquad (7)$$

where,

Re = Reynolds number = $U d_w / v$
U = wind speed (m s^{-1})
v = kinematic viscosity of air
= 1.6×10^{-5} m^2 s^{-1} at 300 K

As noted above, the dependence of the wire temperature on wire diameter and wind speed is contained in h_w.

The solar heating and equilibrium temperature of an external thermocouple wire are given by,

$$Q_s = Q_c = h_w(T_a - T_w) = \alpha_w S/(\pi \cos(45deg)) \quad (8)$$

$$= 220 \text{ W m}^{-2}$$

Where,

α_w = wire solar absorptivity
= 0.7

S = solar insolation on a horizontal surface
= 700 W m^{-2}

Eq (8) includes only direct solar absorption and the cosine term converts solar insolation to direct radiation. Infrared exchange with the cold sky and warm ground are assumed to cancel each other for a net infrared heating of zero. The factor of π reduces the radiation impinging on one side of the wire to an average over the entire wire surface area.

The temperature error of a wire within a naturally-aspirated shield is more complex than for an outside wire because the sensor is shielded from direct solar radiation but absorbs diffuse solar and infrared radiation from the shield plates. In addition, previous studies (e.g., Erell et al, 2005, and Nakamura and Mahrt, 2005) have noted that convective exchange between the sensor and the air can be influenced by atmospheric and plate-generated turbulence. However, only laminar convective heat exchange is assumed in the following discussion as well as an internal air temperature equal to the ambient temperature.

The internal wire temperature is determined from the infrared, solar and convective heating rates,

$$Q_i + Q_s = Q_c \quad (10)$$

Where Q_c can be calculated from Eq. (5), i.e.,

$Q_c = h_{nw} (T_i - T_{wn})$

where,

$T_i = T_a$ = internal air temperature (K)
T_{wn} = wire temperature within a naturally-aspirated shield
h_{wn} = heat transfer coefficient inside the shield.

The infrared heating of the wire is,

$$Q_i = \sigma (T_{pn}^4 - T_{wn}^4)$$
$$= 6 \text{ W/m}^2 \qquad (T_{pn} - T_{wn}) = 1 \text{ K} \qquad (11)$$

Where,

T_{pn} = temperature of the naturally-aspirated plate
σ = Stefan-Boltzman constant
$= 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

A difference of 1 K between the plate and wire temperatures was assumed based on results presented in the next section for a Gill shield in direct sunshine.

The diffuse solar heating rate can be estimated from the studies of Richardson et al. (1999), Hubbard et al. (2001), and Lin et al. (2001). Hubbard et al. determined that the ratio of average solar radiation within the Gill shield to external solar insolation, ε, varied between 7% at noon to 13% at sunrise/sunset. Ray tracing studies of Richardson et al. (1999) indicated that ~10% of external solar radiation penetrated to the center of the shield at a solar zenith angle of 45 degrees. For this calculation a value of 10% for the penetration ratio , ε, was assumed and thus,

$$Q_s = \varepsilon \, \alpha_w S/(\pi \cos(45deg)) \qquad (12)$$

Lin et al. (2001) measured an average internal wind speed of 0.18 m s^{-1} on a wind table and 0.20 m s^{-1} in the atmosphere, for an ambient wind speed of 1.0 m s^{-1}. Richardson et al. found greater wind speed variation with height inside the Gill shield than Lin et al. and an average value of 0.3 m s^{-1} in a wind tunnel with ambient wind speed of 1.0 m s^{-1}. An average wind speed of 0.25 m s^{-1} was selected to encompass the range of results presented by Lin et al. and Richardson et al. The difference between these two studies does not justify specification of the wind speed at a particular height.

The temperature error for a wire within a shield was calculated as a function of wire diameter and solar insolation from Eqs. (10), (11) and (12), and is shown in Fig. 1, along with results for a wire in the open air at 300K.

This figure shows that ~0.3 K accuracy is achievable for a solar flux of 1000 W m^{-2} with a 0.13 mm wire inside the shield, or with a 0.01 mm wire outside the shield. An accuracy of 0.1 K is achievable inside the shield with a 0.04 mm diameter wire. However, since a 0.04 mm wire would experience errors greater than 0.1 K for ambient wind speeds less than 1 m s^{-1}, 0.1 K accuracy cannot be achieved with a naturally-ventilated radiation shield without correction for shield effects. Errors will be even larger if heating of ambient air by the shield itself is included, which is important during light winds. However, during high solar heating and light winds, a convective circulation within the Gill shield is expected which will counteract infrared heating. Experimental verification of this calculation and a temperature correction method are discussed in the next section.

3. Observations

Exposure errors in temperature sensors are commonly studied by comparison to sensors within mechanically-aspirated, shaded, multi-walled tubes. These instruments are commonly assumed to have negligible error (<0.1 K) compared with naturally-aspirated sensors, which can differ from the true atmospheric temperature by 2 K or more. Thus, the sensor error is assumed to be equal to the difference between a well-aspirated sensor and naturally-aspirated sensor. However, except for ideal conditions, mechanically- and naturally-aspirated sensors may differ for reasons other than inadequate ventilation. For example, a mechanically-aspirated sensor has a substantially larger sampling volume during stable conditions than a fine-wire thermocouple. In addition, as noted in Section 1, different response times will cause transient differences. For these reasons, the observations will be presented in terms of temperature differences, and related to true error in the last section. In particular the differences T_{wn} - T_{wa}, and T_{pn} - T_{wn} were measured, where, T_{wn} and T_{pn} were defined in the last section and,

T_{wa} = Temperature of the mechanically-aspirated thermocouple wire.

Except for the wind tunnel test discussed below, T_{wn} and T_{pn} will always refer to temperatures made within the Gill shield with natural aspiration.

Supplementary data were obtained with the Yankee Met-2010 Thermo-hygrometer temperature and dew point sensors, a MetOne 327-C aspirated temperature/dew point instrument, a MetOne two-dimensional sonic anemometer, an Eppley 8-48 radiometer, an Omega 6-14 micron thermocouple infrared sensor, and soil temperature probes, buried 0.025 and 0.152 m below the surface. The Omega infrared sensor has a 60 degree field of view and was pointed northward at a 45 degree angle from the zenith.

The sensor properties are given in Table 1. The thermocouple accuracy is given relative to the reference thermistor.

Sensor	Response time, (seconds)	accuracy
Air temp (T_{wn}) Copper Constantan Thermocouple (0.13 mm)	1	0.03 K, relative
Air temp (T_{wa}), Copper Constantan Thermocouple (0.25 mm)	4	0.03 K, relative
Plate Temp (T_{pn}), Copper Constantan adhesive	10	0.03 K, relative
Wind speed, MetOne 8-48 sonic anemometer	1	0.05 m s^{-1}
Solar radiation, Eppley 8-48	30	20 W m^2
Infrared sky temperature, Omega 6-14 micron	2	18 W m^2 (= 2 K)
Temp/Dew Pt, Yankee Met-2010, (flow rate = 2 m s^{-1}) PRT/chilled mirror	45	0.05/0.2 K
Temp, MetOne 327-C (flow rate = 6 m s^{-1}) , PRT	45	0.1 K

Table 1: Instrument properties.

The relative error of the three thermocouples was found by comparing their 10-minute average temperatures in a wind tunnel with a wind speed of 10 m s^{-1}. This test showed a difference *of* $T_{wn} – T_{wa}$ = - 0.03 K and $T_{pn} – T_{wa}$ = + 0.03 K for the naturally-aspirated wire and Gill plate thermocouples, respectively, with respect to the aspirated thermocouple. These offsets were subtracted from all the data.

Another test of the relative accuracy of the thermocouples was performed in the field experiment during a 5-hour period between 21:30 LT on 25 April and 02:30 LT on 26 April. In this nighttime period the thermocouples differed by less than 0.1 K, the wind speed varied between 2 m s^{-1} and 0.3 m s^{-1}, and the sky and ground temperature were within10 K of the air temperature. For this period $T_{wn} – T_{wa}$ = -0.03 K, which is identical to the value found in the wind tunnel test, and $T_{pn} – T_{wa}$ = -0.02 K, as compared with the wind tunnel difference of +0.03 K. The cooler plate temperature during the field test may be due to radiative cooling of the Gill shield by the sky.

The MetOne 327-C aspiration instrument has greater air flow than the Met-2010 and horizontal plates positioned below the intake opening that prevent the entry of direct radiation and also deflect inflowing air. The reference thermocouple was placed within the Met-2010 rather than in the 327-C because the Met-2010 has a lower specified aspiration error. Long term comparison between its platinum resistance sensor and that in the Met-2010 indicate a root mean square difference of < 0.1 K. Occasionally, however, greater differences are observed. One such period was seen in the field experiment and will be discussed below.

Estimates of the infrared loading of the sensors were based on the surface soil and sky temperatures. The surface soil temperature was found by extrapolating measured temperatures at 0.025 m and 0.15 m below surface level to a depth of 0.0 m. The sky temperature was obtained from a 6-14 micron infrared sensor. The upward and downward nighttime infrared radiation are likely to be over and underestimates, respectively, of their true values. Upward radiation is also a function of the grass temperature, which will be colder and closer to the surface air temperature. The Omega infrared sensor is insensitive to radiation below 6 and above 14 microns, which are optically-thick spectral regions, and hence will radiate at a temperature near that of the air. However, since the infrared radiative forcing is the net radiation (upward – downward), the errors based on soil temperature and 6-14 micron sky radiation will tend to cancel.

The Gill and custom shields were mounted 1.5 m above the ground, at ~ 2 m from the intake to the Met-2010, which contained a 0.25 mm thermocouple,. The instruments were located in the center of a 100 m square grass field. The temperatures were logged at 5-sec intervals with a Campbell Scientific 21x data logger which references the thermocouple temperature to an internal thermistor. To eliminate the difference between the Met -2010 platinum resistance sensor and the 21X thermistor, i.e., to isolate the effects of aspiration only, the thermocouple within the aspiration shield was used as the reference truth.

To assess the effects of the interior flow rate a custom designed 5-plate flat shield was fabricated with the same plate spacing as the Gill shield (1 cm). However, results with this shield were comparable to the Gill shield and will not be discussed further until Section 4.

As noted in the Introduction and shown in Fig. 1, the temperature aspiration error is dependent upon sensor size and can be estimated by comparing the temperatures of thermocouples of different diameters, without the need for auxiliary radiation or wind speed measurements. This possibility was tested by comparing the temperatures of fine, T_f (0.13mm), medium-fine T_{mf}(0.25mm), and coarse T_c (0.8 mm) thermocouple wires placed in the open air. Two days of data with clear skies, a wind speeds of 1-2 m s^{-1} , and an average solar insolation of 600 W m^{-2} were examined to confirm the results in Fig. 1 and to select appropriate sensor sizes to estimate aspiration error The average mid-day value of ($T_f – T_{wa}$) for this period equaled ~0.5 K which is consistent with Fig. 1. The average values of *($T_c – T_f$)* and *($T_{mf} – T_f$)* were approximately 1 K and 0.1 K, respectively, which is also consistent with Fig. 1, but about 50% less than reported by Erell et al. (2005, Fig. 5). However, *($T_c – T_f$)* nearly always had the same sign as ($T_f – T_{wa}$), while the sign of *($T_{mf} – T_f$)* was opposite to ($T_f – T_{wa}$) approximately 25% of the time during the day. For this reason the larger wire was judged to be more reliable for estimating the error of the fine wire thermocouple than the medium-fine wire. In addition, the interior Gill plate (thickness = 1.6 mm) temperature compared favorably with that of the coarse wire thermocouple. Since, the interior plate temperature is of inherent interest it was decided to use it as the second sensor in the estimate of the aspiration error.

Meteorological data for a 7-day observation period in April/May 2008 are shown in Fig 2. This figure shows that the first half of the period had partly cloudy skies, light winds, and a ‘warm’ sky, while the second half had clear, ‘cool’ skies and stronger winds following a frontal passage.

Fig. 3 shows ($T_{pn} – T_{wn}$) and ($T_{wn} – T_{wa}$) during the experimental period. Fig. 3a shows that the plate temperature exceeded the wire temperature within the Gill shield by 0.1 – 0.5 K during the day and was within 0.1 K of the wire temperature most of the time at night.

The difference between the naturally-aspirated and manually-aspirated thermocouples, shown in Fig. 3b, is similar to the Fig. 3a results but slightly larger.

The root-mean-square difference between the naturally-aspirated and aspirated thermocouples for the 7-day period was found to be 0.35C. It was greater in the daytime and less at night, except for anomalous nighttime period on April 29, when ($T_{wn} – T_{wa}$) approached 2 K. The observed daytime difference is comparable to the 0.3 K estimate of the last section.

As noted in previous studies, thermocouple error increases with thermal loading and decreases with wind speed. Nakamura and Mart (2005) combined these two effects into a single non-dimensional ratio of radiation forcing to sensor ventilation.

$$X = Rad/ (\rho\, C_p\, T\, U)$$

Where, Rad equals shortwave or net IR radiation during daytime and nighttime, respectively, and ρ, C_p, T, and U are the air density, heat capacity, temperature and wind speed, respectively. As in Nakamura and Mahrt, ($T_{wn} – T_{wa}$) is calculated as a function of X, for the day and night data. In these calculations the upward infrared flux was calculated from the soil temperature and the downward 6-14 micron flux. These results, shown in Fig. 4, are similar to Nakamura and Mahrt’s Fig. 7 except that the dependence (slope) of X is less. This is because the fine wire thermocouple used here is smaller than, and hence more efficiently ventilated, than the larger sensor tested by Nakamura and Mahrt. The figure also highlights the anomalous nighttime period on April 29 when X ≈ 0.0 and $T_{wn} – T_{wa}$ -> 2.0 K.

The Nakamura and Mahrt forcing parameter is physically based but requires both radiation and wind speed measurements. Since the goal of this paper is accurate temperature measurement without wind or radiation measurements, it is desirable to find an alternate parameter, based only on the temperature measurements. One possibility is to utilize the dependence of error on sensor size shown in Fig. 1. For example, Fig. 1 shows that for a solar insolation of 100 W m^{-2} the error for a 0.5 mm sensor within a Gill shield is 0.2 K while the difference between its temperature and that of a 1.5 mm sensor is 0.3-0.2 = 0.1 K. For a solar insolation of 1000 W m^{-2} the corresponding values are: wire error = 0 .8 K, difference = 1.4 – 0.8 = 0.6. Thus, the difference between the two wire temperatures increases with the fine wire error. This relationship can be exploited by comparing two wire thermocouples of different sizes within a Gill shield. But, as noted above, a more practical alternative is to use an interior Gill plate as the second sensor.

The suitability of ($T_{pn} - T_{wn}$) as an indicator of the thermocouple error is demonstrated with a plot (Fig. 5) analogous to Fig. 4. Fig. 5 shows that ($T_{pn} - T_{wn}$) is a reasonable linear measure of ($T_{wn} - T_{wa}$) during the daytime. At night the correlation is less pronounced but less important since ($T_{wn} - T_{wa}$) is much less.

The dependence of ($T_{pn} - T_{wn}$) on (T_{pn} - T_{wn}) was derived for the observations shown in Fig. 1 and 2. It is desirable to evaluate empirically-derived parameters independently from the data used to derive the parameters. Hence, the 7-day observation period was divided into periods before and after April 29. This division is reasonable because the two periods had different weather and coefficients for each period should be independent of the other.

The data from the first 5 hours of April 29 were not included in the analysis. The reason for this can be seen from Fig. 6, which shows raw thermocouple data as well as temperature measurements (15-min averages) from both the Met-2010 and MetOne 327-C aspirated platinum resistance sensors. The plate temperature is not plotted because it was nearly the same as the naturally-aspirated thermocouple wire, i.e., $T_{wn} \approx T_{pn}$.

The figure shows that T_{wa} is about 1 K less than T_{wn} at 00:00 LT and approaches a maximum difference of 2 K at 03:30 LT. The Met-2010 platinum resistance sensor and aspirated thermocouple temperatures are very similar throughout most of this period. Also significant is the excellent agreement between T_{wn} and the MetOne 327-C platinum resistance sensor during the period, which suggests that the naturally-aspirated thermocouple temperature data is probably an accurate measure of the air temperature and that the difference between the naturally-aspirated and manually-aspirated thermocouples ($T_{wn} - T_{wa}$) may be due to different sampling volumes rather than to inadequate aspiration. Note also that all sensors indicate a rapid decrease in temperature of 1-2 K at 03:15 LT, followed by a rapid increase, which corresponds to a increase in wind speed from near zero to 2 m s^{-}. These results suggests that all sensors are measuring the air temperature with accuracy of less than 0.5 K and that the differences between them are real and not caused by aspiration problems.

The possibility of different sampling volumes for the aspirated and non-aspirated thermocouples is also supported by greater variance seen in the naturally-aspirated thermocouple compared to the aspirated one, and its consistent value during the period, except for the 15-minute period around 3:15 LT, when the wind speed dropped to almost zero. A reason for this is that in a stratified, stable atmosphere with a significant vertical temperature gradient slight (0.05 to 0.1 m) fluctuation in the streamlines will cause significant temperature fluctuations at a point sensor but not in a larger well-mixed volume sampled with mechanical aspiration.

The two aspirated instruments may also have different sampling volumes because of different designs. As noted in the previous section, both instruments have downward facing inflow openings, but the 327-C's opening is blocked by thin, horizontal plates that intercept reflected radiation but also tend to redirect the inflow velocity from upward to horizontal. This redirection will ensure that air entering the intake will originate at approximately the same height as the intake height. On the other hand, since air entering the Met-2010 enters vertically, it may originate from a layer much closer to the ground than its intake entrance height. This could be significant if a cold layer of air is present near the ground.. Thus Fig. 6 suggests reason to doubt that the large value of $T_{wn} – T_{wa}$ for this period is related to aspiration. For this reason, it was not included in the regression.

Regression analysis determined a linear dependence of $(T_{wn} - T_{wa})$ on $(T_{pn} – T_{wn})$ of 1.0 and 0.80, for the first and second periods (before and after April 29), respectively. Corresponding root-mean-square differences for the two periods were 0.21 K and 0.12 K for an average difference of 0.16 K. A plot of the corrected wire temperature obtained with an average coefficient of 0.9 is shown in Fig. 7.

This figure shows that after correction, nighttime temperatures are generally more accurate than daytime temperatures, but anomalously large differences are more likely at night than during the day. These anomalous periods are most likely on stable nights with low morning temperatures. However, as discussed above, these anomalies may be partly caused by factors unrelated to aspiration

4. Discussion and conclusions

The purpose of this work was to develop a method to accurately (<0.1 K) measure the air temperature without mechanical aspiration or supplementary measurements of radiation and wind speed. The approach followed previous suggestions that improved accuracy could be achieved with small sensors, which exchange heat effectively with the ambient air.

Calculations indicate that fine wire thermocouples (~0.1 mm diameter) placed in a radiative shield can yield accuracy of <0.5 K. However, the calculation does not apply in the limit of zero wind when the air temperature within the shield will approach radiative equilibrium with the shield. However, as the shield's temperature varies from the ambient temperature, internal circulation and turbulence will develop and thus a minimum amount of ventilation is expected, even with a near zero ambient wind.

Observations have been analyzed in terms of the difference between a thermocouple in the Gill shield and a mechanically-aspirated, reference thermocouple. This difference includes intrinsic sensor differences, sampling differences, and exposure differences. The intrinsic sensor difference was determined to be 0.03 K from wind tunnel tests and comparison of field data with minimum radiation loading. Temporal sampling differences are assumed to be negligible because the time constants of the thermocouples are much less than the averaging periods. Occasionally, however, volume sampling differences between the references and naturally-aspirated thermocouples of 1 K or more were observed. These periods occurred at night when the mechanically-aspirated instruments sampled a much larger, well-mixed volume than the naturally aspirated thermocouple. A better reference temperature for nighttime comparison would be an ultrafine wire thermocouple, e.g., 0.01 mm in diameter, which could be placed, outside of but very close to the Gill shield.

A correction was determined based on the difference between thermocouple wire and interior plate temperatures that resulted in a root-mean-square difference of 0.16 K over a 7-day observation period. As noted above, the corrected nighttime temperature was generally more accurate than the daytime temperature, except for a few anomalous periods discussed above. Because these anomalous periods are probably due to volume sampling differences between the mechanically-aspirated and naturally-aspirated sensors, the actual accuracy is probably less than 0.16 K. The fast response time of the fine wire thermocouple is not only of inherent value in micrometeorology studies but also provides a valuable measure, e.g. the standard deviation, of extremely low turbulence periods, when aspiration errors could be large.

It was expected that a radiation shield with flat plates would reduce the air flow less than the Gill shield and hence result in a closer equilibrium with the air temperature. Accordingly, a 5-element flat plate shield with identical spacing (1 cm) to the Gill shield was constructed and instrumented as was the Gill shield. This shield produced root mean square errors 10% larger than the Gill shield and higher daytime plate temperatures. Thus, the custom shield was judged to be comparable to the Gill shield but slightly inferior overall, despite the superior ventilation from the flat plate design.

As noted in Section 2, a larger diameter thermocouple wire, could have been used rather than an interior shield plate, for the second temperature. This choice would have several advantages. Both thermocouple wires would presumably obey the same thermal balance relationship and would be exposed to comparable internal infrared and ambient air temperatures. A platinum resistance sensor, with a high absolute accuracy, could serve as the large diameter sensor. However, a much larger sensor would require consideration of its longer response time when comparing with the fine wire sensor.

Previous investigators have suggested other ways to measure the air temperature accurately without continuous aspiration or correction based on collocated wind speed and radiation measurements. Richardson et al. (1999) suggested the use of part-time aspiration. However, this technique would probably require auxiliary measurements of wind or radiation to control fan on and off times. Richardson et al. also suggested the use of a second, smaller, highly reflective sensor beneath a single plate. This approach is similar to the one described here but the sensor is subject to infrared heating or cooling from the surface below the sensor.

Acknowledgements: The author thanks the reviewers for valuable comments that improved the presentation.

References

Collis, D.C. and M.J. Williams (1959), Two-dimensional convection from heated wires at low Reynolds Numbers, *J. Fluid Mech.*, **6**, 357-389.

Erell, E., V. Leal, and E. Maldonado (2005), Measurement of air temperature in the presence of a large radiant flux: An assessment of passively ventilated thermometer screens. *Boundary-Layer Meteor.,* **114**, 205-231.

Friehe, C. A. (1986), Fine-scale measurements of velocity, temperature, and humidity in the atmospheric boundary layer, in *Probing the Atmospheric Boundary Layer*, D. H. Lenschow, ed., 29-38, American Meteorological Society, Boston, MA.

Fritschen, L. J., and L. W. Gay (1979), *Environmental Instrumentation*, Springer-Verlag, New York, 216 pp.

Hubbard, K.G., X. Lin, and E.A. Walter-Shea (2001), The Effectiveness of the ASOS MMTS, Gill, and CRS Air Temperature Radiation Shields*, J. Atmos. Oceanic Technol*., **18**, 851-864.

Lin, X., K.G. Hubbard, and G.E. Meyer (2001), Airflow characteristics of commonly used temperature radiation shields. *J. Atmos. Oceanic Technol*. **18**, 329-339.

Nakamura, R. and L. Mahrt (2005), Air temperature measurement errors in naturally ventilated radiation shields, *J. Atmos. Oceanic Technol*., **22,** 1046-1058.

Richardson, S.J., F.W. Brock, S.R. Semmer and C. Jirak (1999), Minimizing errors associated with multiplate radiation shields. *J Atmos. Oceanic Technol*., **16**, 1862-1872.

List of figures

Fig. 4: Scatter plot of the difference between the naturally-aspirated and mechanically-aspirated thermocouple wire temperatures vs. the radiation forcing. Positive forcing is from shortwave radiation (daytime) while negative forcing is from net infrared (nighttime).

Fig. 5: Scatterplot of ($T_{wn} – T_{wa}$) vs. ($T_{pn} – T_{wn}$) for night (left) and day (right).

Fig. 6: Temperature and wind speed on April 29, 0:00 to 05:00 LT. The heavy dotted and heavy solid lines are the platinum resistance sensors (PRT) in the MetOne 327C and Met-2010 aspirated shields, respectively. The thin solid line is the naturally-aspirated thermocouple in the Gill shield, and the thin dashed line is the thermocouple in the Yankee 2010 shield. The solid line in the lower part of the figure is the sonic anemometer speed. The PRT's are 15-min averages and the thermocouples and sonic speeds are 5 sec samples.

Fig. 7: Temperature difference between the naturally-aspirated and manually-aspirated thermocouples after correction.

List of Tables

Table 1: Instrument properties.

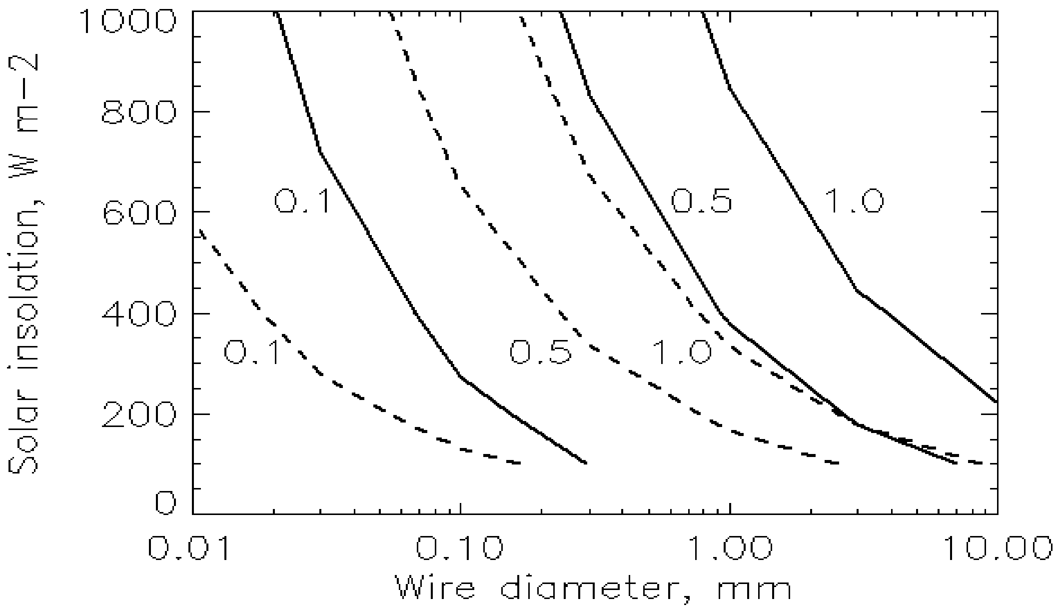

Fig. 1: Sensor error as a function of wire diameter and plate temperature. Contours for 0.1, 0.5 and 1.0 K error are shown for a wire inside (solid line) and outside (dashed line) the shield for an ambient air temperature of 300K, outside and interior wind speeds of 1 m s^{-1} and 0.25 m s^{-1}, respectively.

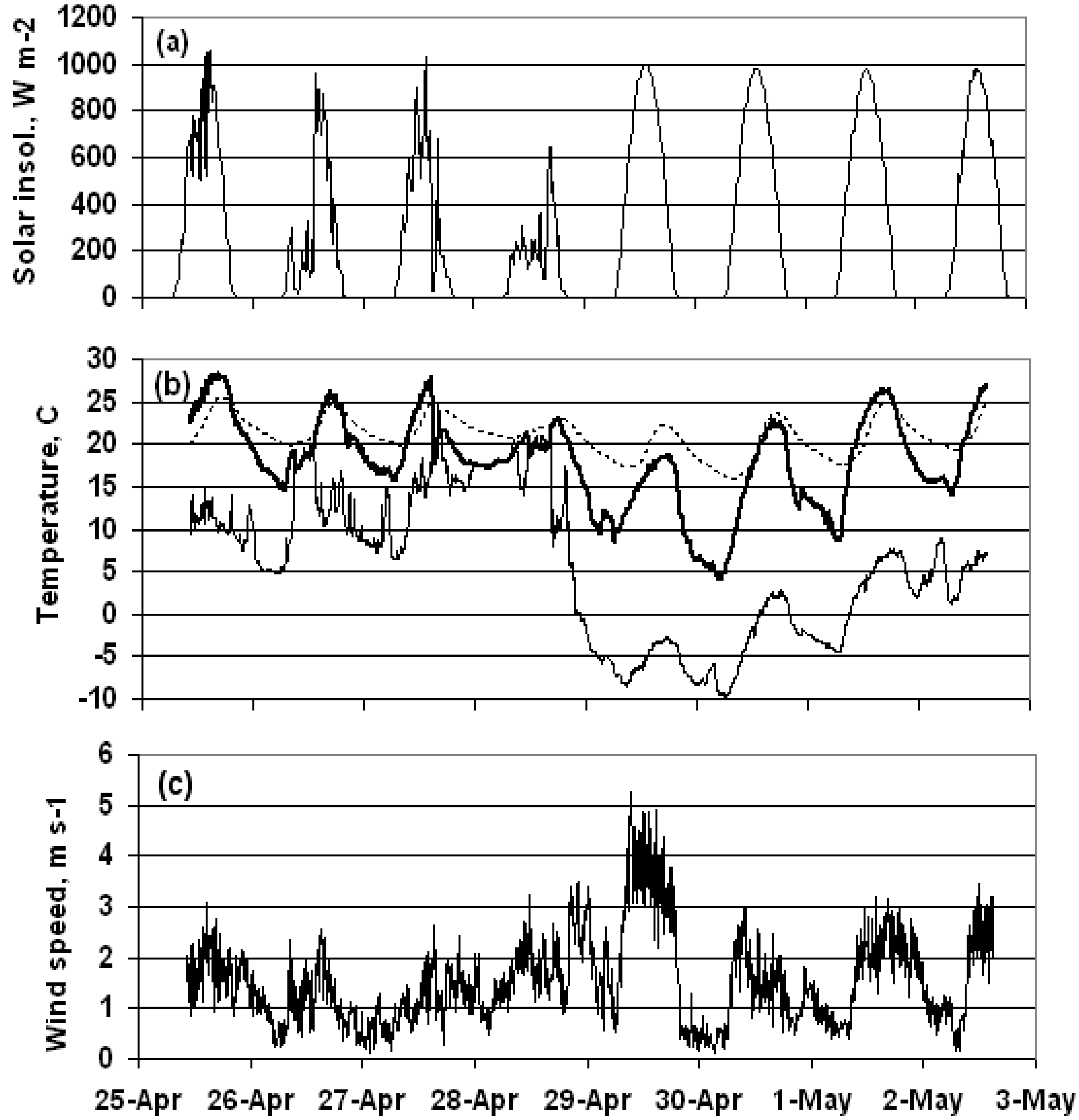

Fig 2: Solar insolation (a), Air temperature (heavy solid), ground temperature (dotted), and sky temperature (thin solid) (b), Wind speed (c).

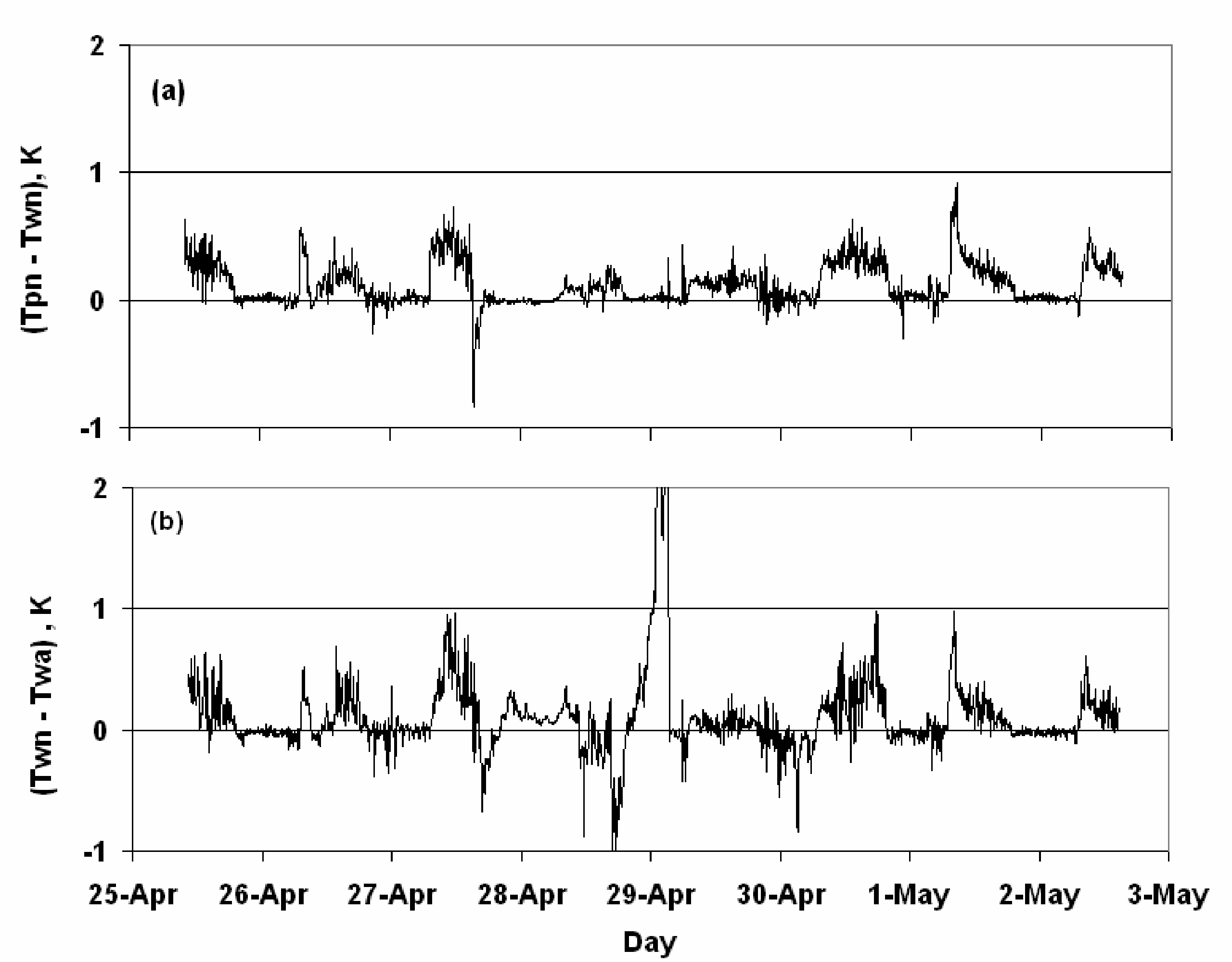

Fig.3: The temperature difference between the Gill plate and the naturally-aspirated thermocouple (a), and between the naturally-aspirated thermocouple and aspirated thermocouple (b)

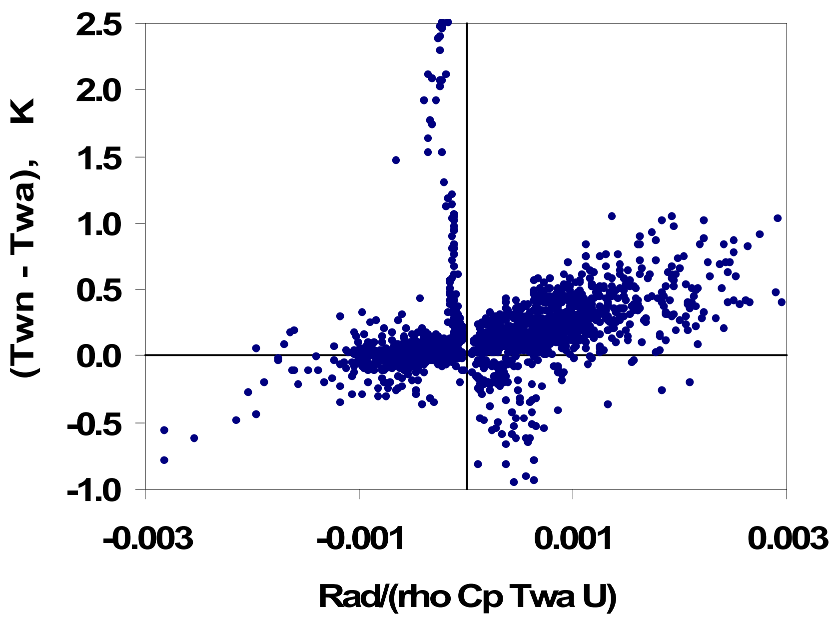

Fig. 4: Scatter plot of the difference between the naturally-aspirated and mechanically-aspirated thermocouple wire temperatures vs. the radiation forcing. Positive forcing is from shortwave radiation (daytime) while negative forcing is from net infrared (nighttime).

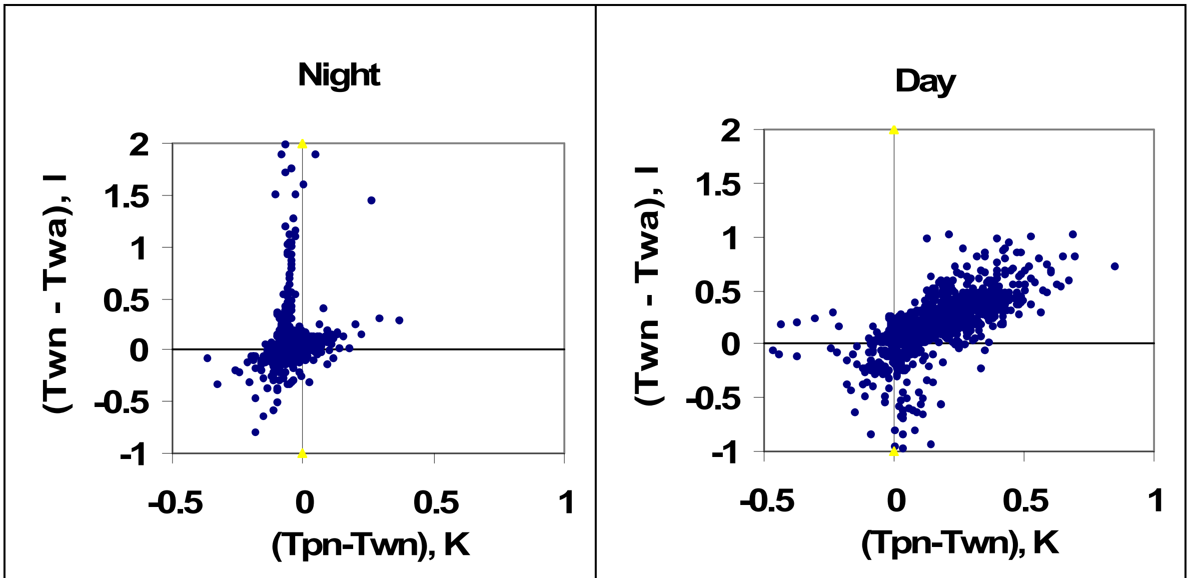

Fig. 5: Scatterplot of ($T_{wn} - T_{wa}$) vs. ($T_{pn} - T_{wn}$) for night (left) and day (right)

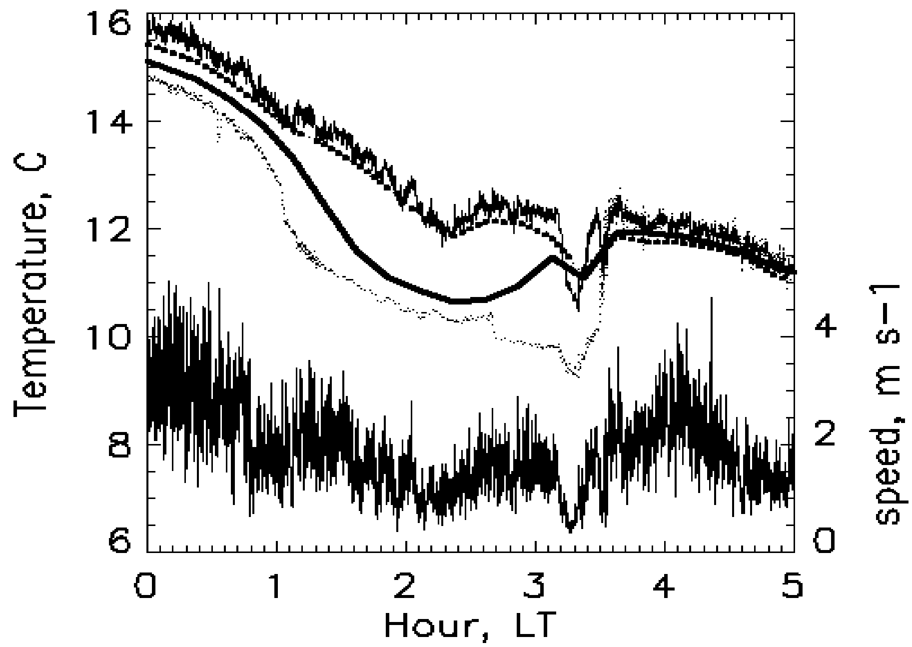

Fig. 6: Temperature and wind speed on April 29, 0:00 to 05:00 LT. The heavy dotted and heavy solid lines are the platinum resistance sensors (PRT) in the MetOne 327C and Met-2010 aspirated shields, respectively. The thin solid line is the naturally-aspirated thermocouple in the Gill shield, and the thin dashed line is the thermocouple in the Yankee 2010 shield. The solid line in the lower part of the figure is the sonic anemometer speed. The PRT's are 15-min averages and the thermocouples and sonic speeds are 5 sec samples.

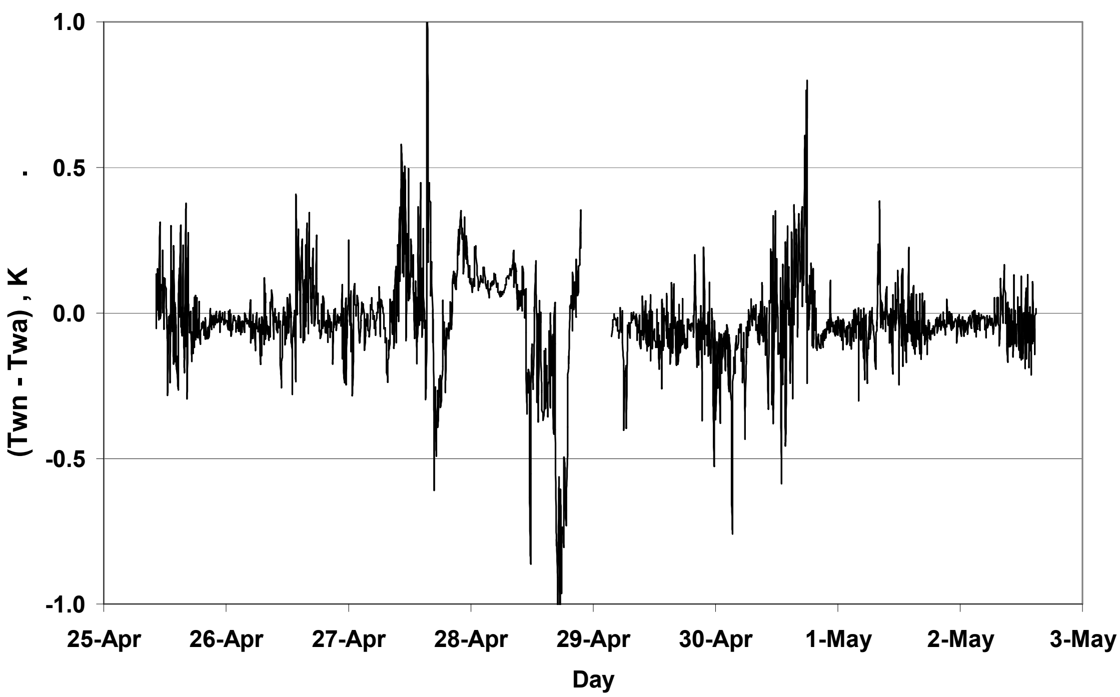

Fig. 7: Temperature difference between the naturally-aspirated and manually-aspirated thermocouples after correction.