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An Improved Method for Correction of Air Temperature Measured Using Different Radiation Shields

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ABSTRACT

The variation of air temperature measurement errors using two different radiation shields (DTR502B Vaisala, Finland, and HYTFZ01, Huayun Tongda Satcom, China) was studied. Datasets were collected in the field at the Daxing weather station in Beijing from June 2011 to May 2012. Most air temperature values obtained with these two commonly used radiation shields were lower than the reference records obtained with the new Fiber Reinforced Polymers (FRP) Stevenson screen. In most cases, the air temperature errors when using the two devices were smaller on overcast and rainy days than on sunny days; and smaller when using the imported rather than the Chinese shield. The measured errors changed sharply at sunrise and sunset, and reached maxima at noon. Their diurnal variation characteristics were, naturally, related to changes in solar radiation. The relationships between the record errors, global radiation, and wind speed were nonlinear. An improved correction method was proposed based on the approach described by Nakamura and Mahrt (2005) (NM05), in which the impact of the solar zenith angle (SZA) on the temperature error is considered and extreme errors due to changes in SZA can be corrected effectively. Measurement errors were reduced significantly after correction by either method for both shields. The error reduction rate using the improved correction method for the Chinese and imported shields were 3.3% and 40.4% higher than those using the NM05 method, respectively.

Key words: radiation shield, measurement error, impacts of solar zenith angle, improved correction method

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1. Introduction

Measurement of air temperature is fundamental to meteorology. Ideally, temperature measurement sensors used to measure air temperature should only exchange heat with the surrounding air. However, in reality the heat from direct solar radiation, reflected shortwave radiation, and sky and terrestrial longwave radiation also affects air temperature sensors (Nakamura and Mahrt, 2005). To avoid these interferences, the World Meteorological Organization provides guidelines on air temperature measurement. They stipulate that air temperature should be measured 1.5–2.0 m above the ground, to avoid the intense variations of temperature close to the ground, and that air temperature sensors should be shielded to avoid direct exposure to radiation. Currently, the HYTFZ01 (Huayun Tongda Satcom Company, China), the DTR502B (Vaisala, Finland) and the BB-1 FRP Stevenson screens (Nanjing Xinhe Xingtai Technology Limited Company, China) are the most widely used radiation shields for measuring air temperature in China. The Stevenson screen is considered to be the standard radiation shield for air temperature measurement sensors in operational meteorological observation practice (CMA, 2003). Both the Chinese and the imported radiation shields are small and easily mounted, and therefore widely used in automatic weather stations. Early studies (Albrecht, 1927, 1934) found that the difference in air temperature measured using the radiation shield and Stevenson screen side by side could be as large as 2°C–3°C. This observation indicates that measured air temperature errors are inevitable even if the sensors are well-shielded. These errors have primarily been ascribed to the radiation and ventilation conditions (Fuchs and Tanner, 1965; Gil, 1983; Tanner et al., 1996; Anderson and Baumgartner, 1998; Richardson et al., 1999; Erell et al., 2005; Arck and Scherer, 2001; Georges and Kaser, 2002; Lundquist and Huggett, 2008).

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Richardson et al. (1999) designed a part-time aspirated multi-plate radiation shield in which a small DC axialvan, Micronel V301M, is inserted into the central opening of the shield, in order to minimize the impact of radiant exchange on the air temperature sensor. Mechanical ventilation is desirable in a radiation shield, although this results in high maintenance costs for long-term operation. Nakamura and Mahrt, (2005, hereafter referred to as NM05) developed an empirical model to correct the radiation-induced temperature error for a naturally ventilated multiplate radiation shield based on observations of wind speed and global solar radiation, in which a data logger (HOBOware Pro manufactured by Onset Computer Corporation, USA) and its external thermistor were enclosed (Whiteman et al., 2000). However, this correction method was not good enough to determine the sensible heat flux, and extreme errors could not be corrected effectively, as the impact of the diurnal variation of solar zenith angle (SZA) on temperature errors was not considered.

Radiation-induced temperature errors from a cube-shaped HOBO radiation shield were considered by Mauder et al. (2008) using the approach of Anderson and Baumgartner (1998). This correction method is better than the NM05 method because it considers the shield's geometric shape, and takes into account the shield's area normal to the sun in addition to solar radiation and wind speed. Previous studies (Richardson et al., 1999; Erell et al., 2005) have suggested that temperature accuracy can be improved by decreasing sensor size. It has been found that smaller sensors, such as a thermocouple constructed of very fine wire, may have an error of only 0.3°–0.5° even when exposed to relatively intense solar radiation. Huwald et al. (2009) found that in addition to natural ventilation, surface-reflected shortwave radiation may be a primary source of error. Robert (2010) assessed and improved the accuracy of air temperature measurements using a Gill radiation shield, without mechanical aspiration, wind speed, or radiation measurements. Instead, he determined a correction based on the difference between the thermocouple wire and interior plate temperatures, and reduced the root-mean-square error to 0.16° over a 7 day observation period

Wang and Han (2008) analyzed the impact of ventilation on reducing radiation-caused air temperature errors by examining two different kinds of devices. They compared a naturally ventilated radiation shield and a positive ventilated radiation shield, with a wooden Stevenson screen under clear-sky conditions in Changchun in July 2007. Their results showed that appropriate ventilation very effectively reduced radiation errors.

In summary, air temperature sensors used in conjunction with radiation shields have certain measurement errors, to which global solar radiation is the leading contributor. Wind speed and SZA also contribute. Although radiation errors could be mitigated by proper construction of a solar radiation shield, e.g., by adding mechanical ventilation, it is uncertain how much this could help. On the other hand, reconstructing solar radiation shields cannot help to improve historical observations. Therefore, it is important to further investigate a correction method to take into account the effects of SZA. This study analyzes a field observations to develop an improved air temperature correction method based on the NM05 approach, with the intention that the improved method could be applied to historical observation data.

2. Field experiment, instruments, and data

The Beijing Meteorological Bureau (BMB) has established over 200 automatic weather stations, where two kinds of frequently-used radiation shields have been installed: the Chinese-made HYTFZ01 and the imported DTR502B models, as listed in Table 1. To characterize the measurement errors from these two shields, parallel observations were conducted using these two devices and a reference Stevenson screen from June 2011 to May 2012 at the Daxing station in Beijing. All three shields were used in combination with the same temperature sensor (HMP45D, Vaisala, Finland).The technical specification is given as following: nominal aaccuracy, type of construction, measurement range and uncertainty are respectively ±0.2°C, Pt 100 IEC 751 1/3 Class B, -40°C to $+60$°C and ±0.13°C. The accuracy of the three sensors was tested at -20°C, -10°C, 0°C, 10°C, 20°C, 30°C and 40°C in a temperature controlled experiment. The temperature readings from the three sensors was within 0.3°C of the true value, and met the precision requirements for air temperature measurement (CMA, 2003).

The field experiment and instrument layout is shown in Fig. 1. The three instruments were installed 1.5 m above ground level. To prevent interference among the devices, they were set separately from each other. The distance between the reference Stevenson screen and the Chinese radiation shield was 5.6 m and the distance between the Chinese and imported radiation shields was 0.4 m. The air temperature was measured every five minutes. These data were stored on a memory card, and regularly submitted to the BMB for analysis. The data were quality controlled, using physical and historical extreme value checks, and also internal, temporal, and spatial homogeneity checks. Error analyses used quality-controlled hourly-averaged datasets.

Table 1. Radiation shield descriptions.

Thermometric device	Type	Sensors
Reference Stevenson screen	New FRP Stevenson screen	HMP45D
Imported radiation shield	DTR502B radiation shield made in Finland, with 9 plates, 20 cm in height, and 5.25 cm dish radius	HMP45D
Chinese radiation shield	Radiation shield made in China, with 19 plates, 23.3 cm in height and 7.05 cm dish radius	HMP45D

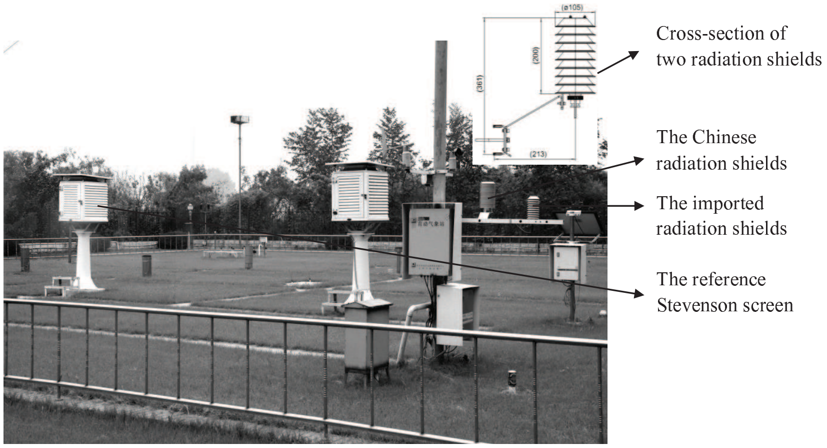

Fig. 1. Layout of the field experiment.

To study the impact of ventilation on temperature errors, wind speed was also observed during the experiment. The wind speed was measured using a wind speed sensor (EL15-1C manufactured by Tianjin Zhonghuan Tianyi Limited Company, China) and the data acquired using a DT50 data acquisition unit manufactured in Australia, as per the work of Wu et al. (2011). There was no solar radiation observation at Daxing station, so hourly global radiation data measured at the nearby Beijing Observatory Station (WMO station No. 54511) were used for correction of temperature errors. The distance between the two stations was 10 km and their underlying surface conditions were similar. Global radiation datasets were tested and processed with the quality control method of Long and Shi (2008). To understand the variation of temperature errors under different weather conditions, the weather conditions from 1 June 2011 to 31 May 2012 were classified into two types: clear days (62 days), and overcast and rainy days (21 days). Clear days had total cloud cover less than 2%, and 0% low cloud cover. Overcast and rainy days had 100% middle and low cloud cover, or more than five hours precipitation.

3. Error characteristics

Figure 2 shows the temporal characteristics of the air temperature measured by the sensor used with the reference Stevenson screen for the 62 clear days. The air temperature measured was in the range −15°C to 35°C and showed diurnal and seasonal variations. The temperature errors between the reference Stevenson screen and the other two devices were investigated by analyzing the measurement datasets. The characteristics of error variations are presented below.

3.1. *Clear-sky conditions*

3.1.1. *Probability distribution*

Figure 3 shows the probability distribution of air temperature errors from the two devices for 62 clear days. The errors measured with both the Chinese and imported radiation shields have a quasi-normal distribution, with ranges of -0.6°C to -0.1°C and -0.5°C to $+0.1$°C. The corresponding errors of the highest probability were between -0.4°C and -0.2°C, and -0.3°C and -0.1°C. This means that temperatures measured with the two devices on clear days were

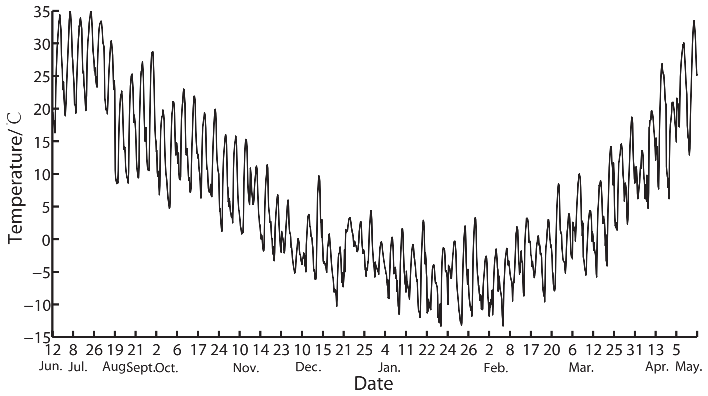

Fig. 2. Temporal variation of the air temperature measured by the reference Stevenson screen from June 2011 to May 2012.

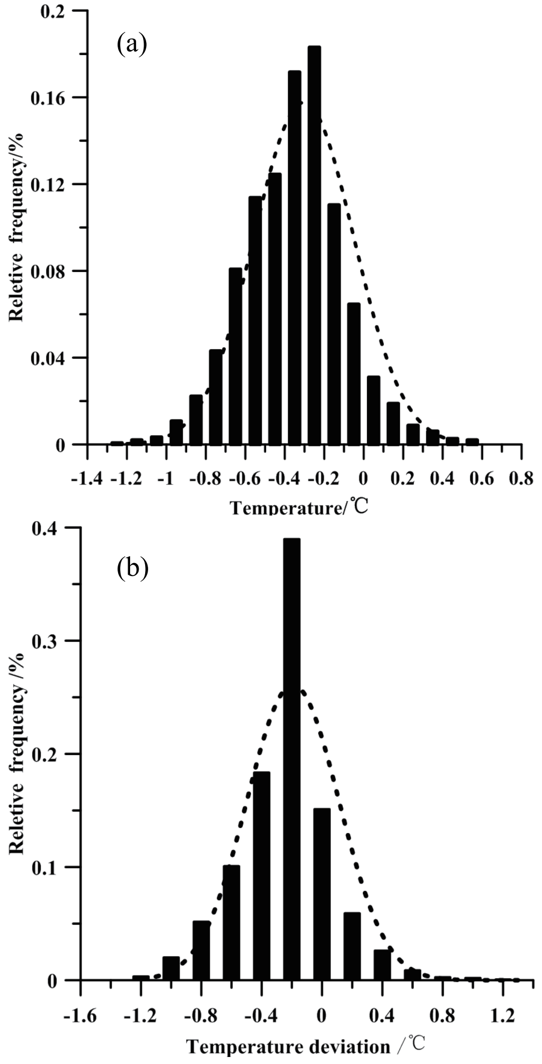

Fig. 3. Probability distributions of air temperature errors from the two radiation shields on the 62 clear days from June 2011 to May 2012: (a) Chinese radiation shield; (b) imported radiation shield.

lower than the reference values in most cases. The results are consistent with those of Erell et al. (2005), who found that nighttime air temperatures measured with Gill radiation shields were up to 1°C lower than if a Stevenson screen was used. The discrepancies in air temperature between the two devices may be attributed to differences in radiative exchange, and to the extent to which the sensors are exposed to natural ventilation. Errors of air temperature measured with the imported radiation shield were smaller than those obtained using the Chinese radiation shield. Table 2 shows the statistical temperature errors from the two devices. The root-mean-square error (RMSE) using the Chinese radiation shield was smaller than that measured with the imported radiation shield, while the reverse was true for the absolute average error (AAE). The maximum and minimum errors of the two instruments were all beyond the ranges of allowable error for temperature measurement, indicating that it is necessary to correct the air temperatures measured using these two shields.

3.1.2. *Diurnal variations*

Figure 4 shows the diurnal variation characteristics of the monthly average air temperature error using the two devices under clear-sky conditions. Generally, most of the errors when using the Chinese radiation shield were negative during the daytime. AAE using the Chinese radiation shield started to increase at sunrise, reached its maximum at noon, maintained a higher value in the afternoon and began to decrease at sunset. In contrast, the monthly average errors for measurements conducted with the imported radiation shield during the daytime were positive, with a range of 0°C to 0.6°C. Those at night, however, were negative, from -1.0°C to 0°C. Consequently, air temperatures measured using the imported radiation shield were higher than the reference values during most of the daytime and lower at night. Similarly, AAE from the imported radiation shield increased at sunrise, reached a maximum at noon, maintained a higher value in the afternoon, and began to decrease during 1500 to 1600 LST (Local Standard Time), and reached a minimum at sunset. Diurnal variation characteristics of temperature errors from the two devices are clearly related to the diurnal variation of solar radiation, discussed further below.

3.2. *Overcast and rainy days*

3.2.1. *Probability distribution*

Figure 5 shows the probability distributions of the temperature errors from the two devices during the 21 overcast and rainy days. Error distributions from the Chinese and imported radiation shields on the overcast and rainy days both follow a quasi-normal pattern, primarily distributed in the ranges -0.6°C to -0.3°C and -0.4°C to -0.1°C. The corresponding errors of the highest probability fall within -0.5°C to -0.4°C and -0.3°C to -0.2°C. This means that the air temperatures measured by the two devices were lower than the reference values in most overcast and rainy cases, especially with the Chinese shield. Errors of measured air temperature using the imported radiation shield on overcast and rainy days were smaller than measurement errors with the Chinese shield in most cases. Air temperature measurement errors using the two devices on overcast and rainy days were smaller than those under clear-sky conditions. This is

Table 2. Temperature error statistics of the two devices before correction on the 62 clear days between June 2011 and May 2012.

Thermometric devices	RMSE (°C)	AAE (°C)	Maximum error (°C)	Minimum error (°C)
Chinese radiation shield	0.21	0.53	0.70	−1.20
Imported radiation shield	0.28	0.22	1.30	−0.90

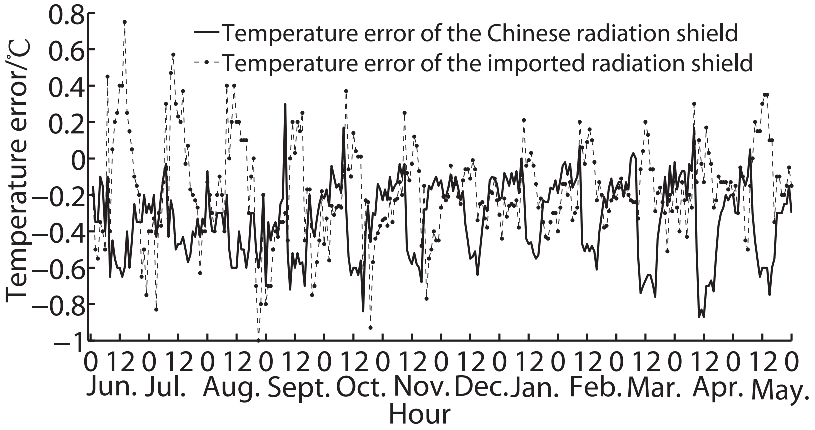

Fig. 4. Diurnal variation of the monthly average error on the air temperature measurement using the two radiation shields under clear-sky conditions from June 2011 to May 2012.

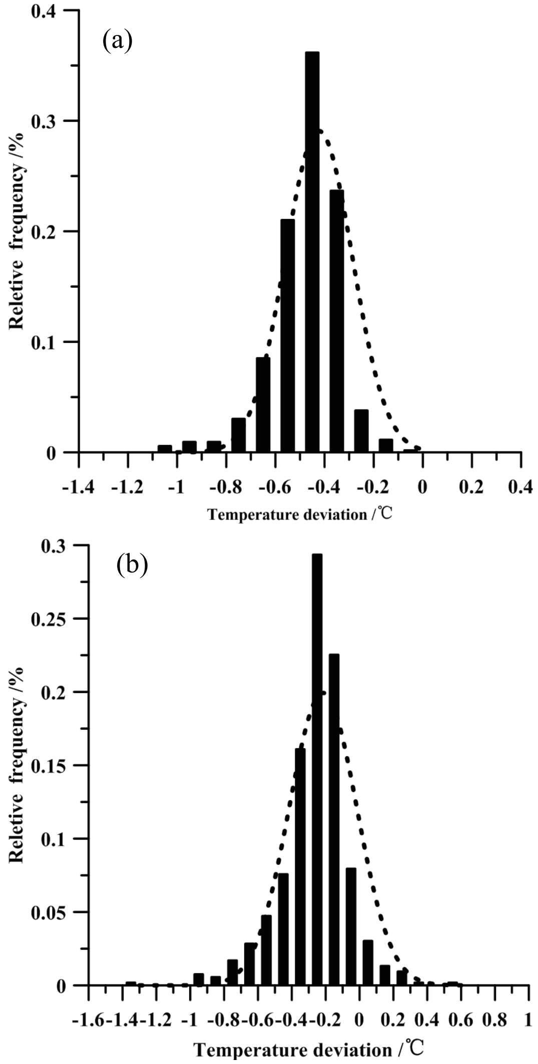

Fig. 5. Probability distributions of air temperature errors from the two radiation shields on the 25 overcast and rainy days from June 2011 to May 2012: (a) Chinese radiation shield; (b) imported radiation shield.

because global solar radiation on overcast and rainy days is less intense than under clear-sky conditions.

3.2.2. *Diurnal variations*

Figure 6 shows the diurnal variation of monthly averaged air temperature errors from experiments using the two shields on the overcast and rainy days. Monthly averaged errors were in the range $-0.6°C$ to $0.0°C$. Air temperatures measured using the two radiation shields were lower than the reference temperature values obtained using the Stevenson screen. Diurnal variations of the monthly averaged errors from the two devices were similar to those under clear-sky conditions, but error distributions on overcast and rainy days were narrower than those on sunny days, especially for the imported shield.

4. Primary influencing factors

As mentioned above, the direct shortwave radiation and ventilation are major factors influencing the accuracy of air temperature measurements. The impacts of global solar radiation and wind speed on errors resulting from the two devices are discussed in this section. Figure 7 shows scatter diagrams of the hourly errors of air temperature measurements performed with the Chinese and imported radiation shields, along with global solar radiation [panels (a) and (b)] and wind speed [panels (c) and (d)] during the daytime portions of the 62 clear days. Temperature error varies with both the global solar radiation and wind speed. The correlations between the errors for the two devices, global radiation, and wind speed are significant and nonlinear. The correlation coefficients for the Chinese radiation shield are slightly higher than those for the imported shield.

5. Correction methods

In NM05, the authors proposed a method for correction of air temperature error based on observational data of global solar radiation, R, wind speed, U, and air temperature, T.

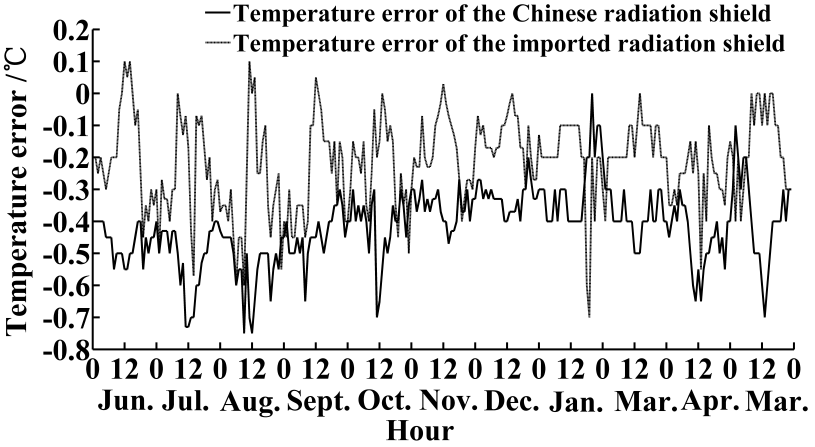

Fig. 6. Diurnal variation of the monthly average error on the air temperature measurements using the two radiation shields on the 25 overcast and rainy days from June 2011 to May 2012.

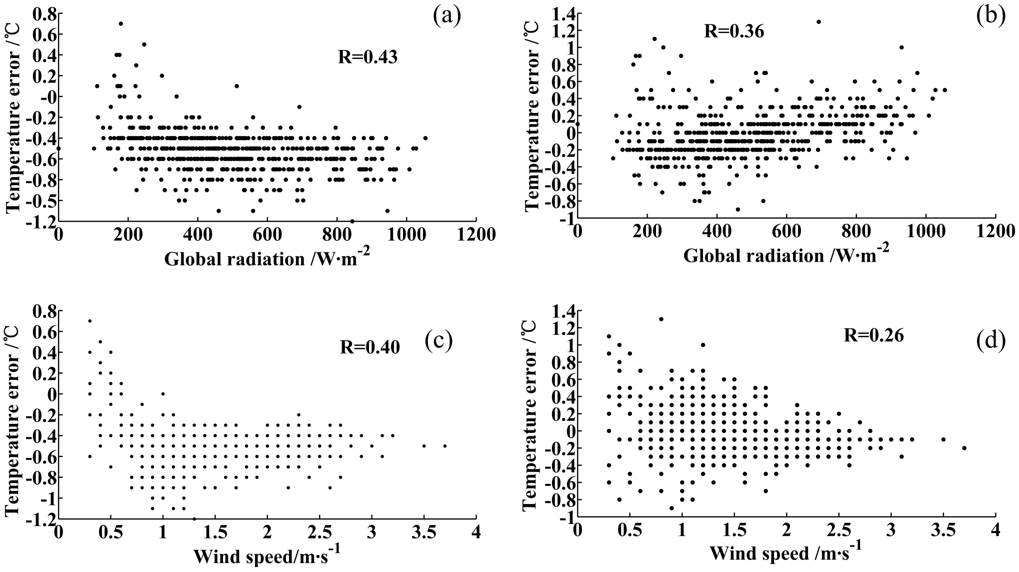

Fig. 7. Scatter diagram of correlations between the errors from the imported and Chinese radiations shield and global solar radiation and wind speed in the daytime of the 62 clear days from June 2011 to May 2012: (a) errors of the Chinese radiation shield against global radiation; (b) errors of the imported radiation shield against global radiation; (c) errors of the Chinese radiation shield against wind speed; (d) errors of the imported radiation shield against wind speed.

They defined a non-dimensional parameter, X, in order to represent the effect of these three variables:

$$X = \frac{R}{\rho c_p T U} \ . \tag{1}$$

Here, ρ is the density of air, taken to be 1.29 kg m^{-3} when the pressure and temperature is respectively 1013.25 hpa and 25°; c_p is the heat capacity of air at constant pressure, taken as 1004 J K^{-1} kg^{-1}; R is in W m^{-2}, T is in K, and U is in m s^{-1}.

The previous section discussed how air temperature errors changed sharply at sunrise, noon, and sunset, an effect clearly related to the variation of the solar zenith angle. Based on the method of NM05, the impact of solar zenith angle on air temperature errors was accounted for using

$$X_{\rm n} = \frac{R}{\rho c_p T U} \frac{Z}{180} \ , \tag{2}$$

where $X_{\rm n}$ is a new non-dimensional parameter and Z is the solar zenith angle in degrees. Nakamura and Mahrt (2005) tried to fit the error of temperature in term of polynomial function of X,

$$\Delta T = a + bX \ , \tag{3}$$

where ΔT is temperature error, and X is the non-dimensional parameter defined by Eq. (1). The linear correction model was established using historical data. Since errors from the two radiation shields at night on clear days were smaller than those during the daytime, the above two methods were used to correct errors of air temperature during the daytime only. Temperature datasets measured by the two devices on 57 days from 1 June 2011 to 31 March 2012 were used to establish linear correction models, while the measurement data from the other five days in April and May 2012 were applied to test the corrected results.

Table 4 shows correlation coefficients and fitting coefficients for the two methods using 480 samples from 57 clear days. For the Chinese radiation shield, the correlation coefficient and slope of the fitting model obtained using Eq. (1) were all smaller than those using Eq. (2). For the imported shield, the correlation coefficient using Eq. (1) was larger than that using Eq. (2), while the reverse was true for the slope of fitting model.

Using the results from the four correction models summarized in Table 3, air temperature errors from the two devices were corrected for the daytime records for five clear days in April and May 2012. Figure 8 shows the diurnal variation of the absolute errors before and after correction. Errors after correction were reduced significantly, especially at sunrise, noon, and sunset. For example, errors from the imported radiation shield, which were greater than 0.5°C on several occasions before the correction, were all reduced to less than 0.3°C when corrected by the NM05 method, and 0.16°C when corrected by the modified method. Figure 8 also shows that the correction outcome with the improved method was better than that using the NM05 method. Error statistics both before and after correction using the two methods are given in Table 4. The mean errors from the two devices corrected using both methods are decreased significantly, especially for the imported shield. Defining an error reduction rate r as

$$r = \frac{E_{\mathrm{bc}} - E_{\mathrm{ac}}}{E_{\mathrm{bc}}} \times 100\% , \tag{4}$$

where E_{bc} is error before correction and E_{ac} is error after correction, allows assessment of the performance of the two correction methods. The r values are listed in Table 4, where it is seen that the R values for the current method were greater than those for NM05, indicating the current scheme performed better. The r values for measurements with the imported shield were larger than for measurements with the Chinese shield. This is likely because the gap between the two plates of the imported radiation shield was larger than that of the Chinese shield, so when the solar zenith angle was large at sunrise or sunset, more solar radiation passed through the gap and heated the sensor. Thus, the impact of solar zenith angle on air temperature errors with the imported radiation shield was more significant. This demonstrates the necessity of considering the effect of solar zenith angle on the correction of measured air temperature.

6. Conclusions

In this paper, the error characteristics of air temperature measured using the two kinds of thermometric devices, and with two different correction methods applied, were studied. The results showed that most of the air temperatures measured using the Chinese and imported radiation shields were lower than the reference measurements using the Stevenson screen, most likely due to the difference in radiative exchange between the two kinds of devices and to the extent to which the sensors are exposed to natural ventilation. The error distributions of the two devices had ranges of −0.6°C to −0.1°C and −0.5°C to +0.1°C, respectively. The maximum (positive during daytime) and minimum (negative during nighttime) errors using the two instruments were 0.70°C and 1.30°C, and −1.20°C and −0.90°C, respectively. In general, errors associated with the two devices on the overcast and rainy days were smaller than those under the clear-sky conditions. Temperature errors with the imported radiation shield were smaller than those with the Chinese shield in most cases.

The air temperature errors from both devices changed sharply at sunrise and sunset, and reached maximum values at noon. Diurnal variation characteristics of the errors were

Table 3. Results of fitting models for the two devices for the daytime during the 57 clear days from June 2011 to March 2012.

	NM05's method		This paper's method	
Thermometric devices	Correlation coefficient	Fitting formula	Correlation coefficient	Fitting formula
Chinese radiation shield	0.03	$\Delta T = -0.02X - 0.49$	0.26	$\Delta T = 0.44X - 0.61$
Imported radiation shield	0.48	$\Delta T = 0.30X - 0.32$	0.17	$\Delta T = 0.40X - 0.11$

Note: ΔT is error in air temperature, and X is the non-dimensional quantity.

Table 4. Error statistics before and after correction using the two methods for both radiation shields in the daytime of the five clear days in April and May 2012.

Thermometric device	MEBC (°C)	MEAC by the NM05 method (°C)	MEAC by this paper's method (°C)	r by the NM05's method (%)	r by this paper's method (%)
Chinese radiation shield	0.60	0.52	0.49	13.68	16.98
Imported radiation shield	0.21	0.14	0.06	31.83	72.24

Note: MEBC is mean error before correction; MEAC is mean error after correction; r is reduction rate.

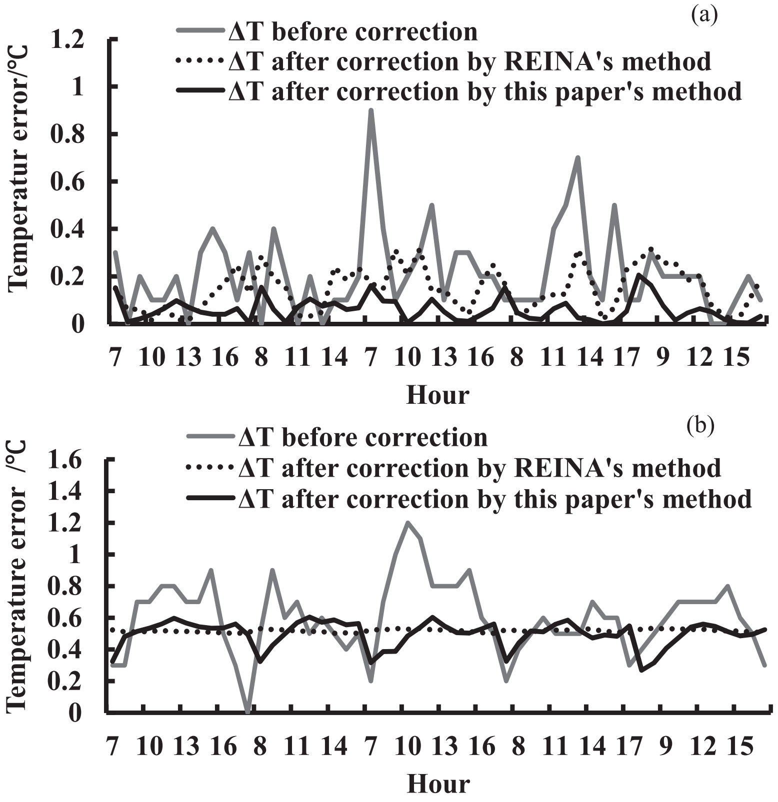

Fig. 8. Diurnal variation characteristics of the absolute air temperature errors from the two radiation shields before and after applying the two correction methods for the daytime of the five clear days in April and May 2012: (a) imported radiation shield; (b) Chinese radiation shield.

found to be related to the diurnal variation of the solar radiation. The major influencing factors for air temperature errors during the daytime on clear days are global solar radiation and wind speed. The relationship between the errors and the influencing factors was found to be nonlinear. We modified the NM05 method by accounting for the effect of the solar zenith angle on air temperature measurements. The extreme errors at sunrise, noon, and sunset were effectively corrected by this modified method. The original NM05 scheme and the modified scheme were applied to correction of the errors of temperature measurements using Chinese and imported radiation shields. Most measurement errors for both devices were reduced significantly, especially for the measurements at sunrise, noon, and sunset. The reduction rate (R) of errors for the Chinese and imported shields using the modified correction method were found to be 3.3% and 40.4% higher than those using the NM05 method, suggesting that the correction method proposed in this paper improves on the NM05 approach. This is largely due to accounting for the solar zenith angle, which significantly impacts air temperature error. It should be noted that the correction factor ($Z/180$) in the modified correction expression may be zero at certain times of the year between the Tropic of Capricorn and Tropic of Cancer. Thus, the improved correction method is mostly suitable for subtropical and higher-latitude regions.

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