Temperature error-correction method for surface air temperature data

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Abstract
In climate change research, accurate temperature data are often demanded. However, affected by many factors, especially solar radiation, the accuracy of environmental air temperature measurement can be greatly reduced, since there is a difference in temperature between the environmental air and the related temperature measured by the sensor accommodated inside the radiation shield. In the paper, the term “temperature error” refers to the temperature difference described above. To improve the accuracy of the temperature data, a temperature error-correction method is proposed. First, a computational fluid dynamics (CFD) method is adopted to quantify the temperature errors accurately. A neural network algorithm is then applied to form a universal correction equation by fitting temperature errors calculated using the CFD method. Finally, to validate the correction equation, field observation experiments are performed. The root mean square error (RMSE) and the mean absolute error (MAE) between the temperature errors obtained experimentally using a sensor inside the DTR503A shield and the corresponding temperature errors determined by using the proposed correction method are 0.043 and 0.038 °C, respectively. The RMSE and MAE for the DTR13 radiation shield are 0.049 and 0.044 °C, respectively. This method may reduce the error of the temperature data to 0.05 °C. If the environmental factors corresponding to the temperature data can be quantified accurately, the factors influencing the temperature error can be added to the correction method continuously. The accuracy of this correction method may be furtherly improved.

KEYWORDS
climate change, computational fluid dynamics, correction method, neural network algorithm, temperature data, temperature error

1 | BACKGROUND AND MOTIVATION

The explosion of interest in climate change has been driven by global warming, and related issues have been widely discussed by government organizations and the public around the world. The Intergovernmental Panel on Climate Change (IPCC) stated that the mean increase in temperature during the 20th Century was 0.006°C-year⁻¹.¹ In 2018, a representative IPCC report indicated that limiting the global temperature increase to 1.5°C could go hand in hand with pursuing a more

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environmentally friendly and sustainable society. In other words, by 2100, we should reduce the mean increase in temperature to < 0.019°C-year^{-1}.2 Fyfe et al. (2013) concluded that the global mean temperature increased at a rate of 0.14 ± 0.06°C-decadet^{-1} by analysing the data in the period 1993–2012. Dillon et al. (2010) analysed the data in the period 1961–2009 and concluded that the temperatures in tropical areas and in the Northern Hemisphere areas increased by approximately 0.4 and 0.95°C, respectively. Gleisner et al. (2015) evaluated that the temperature increased by 0.8°C by analysing the data over the past 30 years (1979–2013).

The accuracy of the temperature data is affected by the measurement set-up, calibration uncertainties of the used instruments, stability (drift) of the instruments and radiation. Some corresponding methods are adopted to improve temperature measurement accuracy. A resistance bridge circuitry system is designed with improved precision and stability. The circuitry can achieve up to 1–10 ppm repeatability under typical outdoor environment. With a 0.05 PPM-K^{-1} low temperature coefficient of resistance (TCR) reference resistor, electronics noise on the order of 0.001°C and repeatability on the order of 0.005°C or even lower have been observed with this circuit. In addition, like high-end thermometer bridges, the measurement current can be significantly smaller than 1 mA, thus the self-heating of the probe can be considered negligible. Four air temperature sensors used in the experimental part of the study were calibrated by a comparison method by using a high-precision standard platinum resistance thermometer (SPRT) as a reference sensor. The SPRT was calibrated directly in temperature fixed-point cells. By using this approach, the uncertainty of the calibration of air temperature sensors can be reduced to approximately 0.01°C.

However, the temperature error induced by the radiation is more significant (Lin et al., 2001b; Perry et al., 2007; Holden et al., 2013; Lopardo et al., 2014; Rajczak et al., 2015). Harrison and Wood concluded that the structure of a shield or a screen reduces the exchange of the internal and external air (Harrison, 2011; Harrison and Wood, 2012). Because the temperature of the shield or the screen is higher than that of the air due to solar radiation, the surrounding air is heated before going into the shield or the screen. The temperature of the internal air is higher than that of the external air. Hence, there is a difference between environmental air temperature and the temperature measured by using a sensor accommodated inside a shield or a screen. Much research has focused on improving the performance of shields (Hubbard et al., 2001; Meulen and Brandsma, 2008). The temperature error is also affected by many other factors, including airflow (Lin et al., 2001a), radiation (Lin et al., 2001b) and the underlying surface (Lin et al., 2005). In addition, to improve temperature measurement accuracy or to reduce the cost, various shields have been designed. For instance, Erell et al. (2005) proposed several shields and evaluated them experimentally. The experimental results indicated that the temperature errors observed when using these shields were up to 0.8°C. Hubbart (2011) evaluated a new shield under cloudless conditions. The experimental results indicated that the mean temperature error with this new shield was 2.84°C.

In conclusion, even if a high-accuracy sensor were used for temperature measurement, temperature errors will be still present in the historical temperature data. Hence, a correction method may be needed.

The World Meteorological Organization (WMO) report pointed out that it is necessary to investigate wind attenuation ratio modeling and to estimate the temperature error with the help of a computational fluid dynamics (CFD) method (Hatton & Jones, 1998). CFD is a multi-physics numerical computation method (Mahajan et al., 2005; Esfe et al., 2014). Richardson (1995) obtained the internal and external airflow fields of a Gill shield with the help of the CFD software package Fluent. Due to limited maturity of the CFD method in the 1990s and early 2000s, the heat transfer model of the Gill shield cannot be constructed. Hence, the temperature fields of the Gill shield cannot be obtained. However, with the development of software and improvements in computer performance, Fluent has been able to calculate the fluid–solid coupled heat transfer accurately, thereby obtaining a more accurate temperature field distribution and temperature error.

The paper proposes a temperature error-correction method. First, the CFD method is used to quantify the temperature errors for the DTR503A and DTR13 radiation shields under a variety of conditions. A neural network algorithm is then adopted to form a universal temperature error-correction equation by fitting temperature errors calculated using the CFD method. Finally, to validate the correction equation, the corresponding field observation experiments are performed. During the experiments, four calibrated sensors are installed in a DTR503A shield, a DTR13 shield, a 43502 aspirated radiation shield and a 076B aspirated radiation shield, respectively. During the daytime, due to the influence of radiation, the measured temperature is higher than the external free air temperature. The smaller air temperature of the two aspirated radiation shields served as an air temperature reference. The temperature error-correction method may potentially be used to correct the temperature data.
2 | TEMPERATURE ERROR-CORRECTION METHOD

2.1 | Construction of the CFD models

To quantify the temperature error for the sensors inside a DTR503A shield and a DTR13 shield, two corresponding CFD models are constructed. The diameter of the plate, the height of the shield and the distance between the adjacent plates of the DTR503A shield are 105, 266 and 22 mm, respectively. The diameter of the plate, the height of the shield and the distance between the adjacent plates of the DTR13 radiation shield are 220, 299 and 23 mm, respectively. A PT100 thin-film platinum resistance thermometer (M222, Heraeus Holding GmbH, Germany) is mounted in a central position in the shield (Figure 1).

Although the large size of the air domain is beneficial to improve the numerical solution accuracy, it also leads to computation complexity. It is concluded that the reasonable air domain size is $3,500 \times 3,000 \times 7,000$ mm by comparing models with a variety of air domains.

The tetrahedral meshes of the two models are obtained by using the CFD software package ICEM (Davis, 2015; Huang et al., 2017). The numbers of tetrahedral elements of the DTR503A shield and the DTR13 shield are 1,572,374 and 1,572,374, respectively. These models are made in three dimensions. The quality values of the meshes are $> 0.35$. To obtain the temperature and velocity fields, the CFD software package Fluent is applied (Kumar and Kim, 2016; Baghapour and Sullivan, 2017 Qian et al., 2018). A standard SIMPLE algorithm, a standard initialization method, a $k-\varepsilon$ model and a solar ray tracing algorithm are used in the CFD model (Stafford et al., 2012). In addition, the boundary condition parameters are set according to the actual environment.

2.2 | Numerical calculation of temperature errors

To quantify the measurement error of the environmental air temperature when using DTR503A or DTR13 shields and corresponding temperature sensors, these CFD models are analysed under different environment conditions, including air velocity $V$, solar short wave radiation strength $P_1$, upwelling long wave radiation strength $P_2$, sun elevation angle $E$, altitude $A$, underlying surface reflecting ratio $f_1$ and the coating reflecting ratio of the shield $f_2$. The values for $V$, $P_1$, $P_2$, $E$, $A$, $f_1$ and $f_2$ are $0.5$ m/s, $1000$ W/m$^2$, $300$ W/m$^2$, $45^\circ$, $0$ km, $0.2$ and $0.87$, respectively. The temperature and velocity fields of these CFD models under this environment condition are shown in Figure 2.

Air velocity decreases by approximately $50\%$ and $75\%$ inside both the DTR503A and DTR13 radiation shields, respectively (Figure 2b, d). Because the temperature error is closely related to air velocity, the temperature error for the DTR13 radiation shield is greater than that for the DTR503A. The temperature errors for the DTR503A and DTR13 are $0.279$ and $1.586$ $\degree$C, respectively (Figure 2a, c). Hence, the uncertainties related to environmental air temperature measurements, performed by using a DTR503A or a DTR13 shield, might be significantly higher than the calibration uncertainties of the temperature sensors accommodated inside the respective shields. The initial temperatures of the free air, thin-film platinum resistance thermometers, and DTR503A and DTR13...
shields are set to 300 K in these CFD models. To verify that the temperature error is slightly affected by environment temperature, several simulation studies are implemented under different environment temperatures of 273, 283, 293, 300, 310 and 320 K. Because the intensity of the emitted long wave radiation from the air, thermometer, and DTR503A and DTR13 shields is much lower than that of the direct solar radiation, upwelling long wave radiation and reflected solar radiation, this emitted radiation is ignored to simplify the CFD model and, consequently, to decrease the computation time. The CFD results are shown in Table 1.

To obtain accurate temperature data provided by these two shields in future, we can reduce the temperature error by optimizing and improving their structures. However, the historical temperature data provided by these two shields still have temperature errors. Hence, it may be advantageous to use a temperature error-correction method to correct the historical temperature data obtained by using these two shields.

First, the temperature errors related to the use of DTR503A or DTR13 shields and corresponding temperature sensors under various environmental conditions need to be quantified accurately with the help of the CFD method. The default values for $V$, $P_1$, $P_2$, $E$, $A$, $f_1$ and $f_2$ are $0.5 \text{ m/s}^{-1}$, $1000 \text{ W/m}^{-2}$, $300 \text{ W/m}^{-2}$, $45^\circ$, $0 \text{ km}$, $0.2$ and $0.87$, respectively. The ranges for $V$, $P_1$, $P_2$, $E$, $A$, $f_1$ and $f_2$ are $0.5$–$8 \text{ m/s}^{-1}$, $200$–$1000 \text{ W/m}^{-2}$, $100$–$500 \text{ W/m}^{-2}$, $10$–$90^\circ$, $0$–$5 \text{ km}$, $0.1$–$0.9$ and $0.5$–$0.9$, respectively. The quantized temperature errors are shown in Figures 3 and 4.

The temperature error decreases when increasing $V$ and $f_2$. The temperature error increases when increasing $P_1$, $P_2$, $A$ and $f_1$. When $P_1$ is $200$ and $1000 \text{ W/m}^{-2}$, the
The temperature errors are 0.101 and 0.279°C, respectively (Figure 3a). When \( P_2 \) is 100 and 500 W·m\(^{-2} \), the corresponding temperature errors are 0.242 and 0.317°C (Figure 3b). When \( A \) increases from 0 to 5 km, the temperature error increases from 0.279 to 0.487°C (Figure 3c). When \( E \) is 10 and 90°C, the temperature errors are 0.297 and 0.1°C, respectively (Figure 3d). When \( f_1 \) changes from 0.1 to 0.9, the temperature error increases from 0.261 to 0.41°C (Figure 3e). When \( f_2 \) changes from 0.5 to 0.9, the temperature error increases from 0.289 to

FIGURE 3 Temperature errors for the temperature sensor equipped with a DTR503A radiation shield calculated using the computational fluid dynamics (CFD) method under the conditions of various environmental factors.

FIGURE 4 Temperature errors for the temperature sensor equipped with a DTR13 radiation shield calculated using the computational fluid dynamics (CFD) method under the conditions of various environmental factors.
0.161°C (Figure 3f). The temperature errors calculated for
the DTR13 radiation shield (Figure 4) are similar to those
calculated for the DTR503A radiation shield. However,
due to relatively good ventilation and a relatively slight
heat conduction, the temperature errors shown in
Figure 3 are smaller than those shown in Figure 4.

2.3 Construction of temperature error-correction equations

Because it takes about 10 min to calculate a group of
values when using a computer with high processing
speed, it is almost impossible to correct temperature data
only through the CFD method. Therefore, an accurate
and effective correction equation is needed. The neural
network algorithm is used to fit the limited CFD
temperature error results to obtain the temperature
error-correction equation. The three-layer neural
network algorithm topology is shown in Figure 5.

As shown, there are seven neurons in the input layer,
n neurons in the hidden layer and one neuron in the out-
put layer. \( \Phi \) and \( \varphi \) are the activation functions of the hid-
den and output layers, respectively. \( P_1, P_2, V, E, A, f_1 \) and
\( f_2 \) are the neurons of the input layer. \( w_{ij} \) is a weight from
the \( i \) neuron of the hidden layer to the \( j \) neuron of the input
layer. \( \theta _i \) is a threshold of the \( i \) neuron of the hidden layer.
\( w_{ki} \) is a weight from the \( k \) neuron of the output
layer to the \( i \) neuron of the hidden layer; \( k = 1 \). \( \alpha_k \) is a
threshold of the \( k \) neuron of the output layer. \( O_k \) is an
output of the \( k \) neuron of the output layer.

The correction equation among the temperature error
\( \Delta T \), \( P_1 \), \( P_2 \), \( V \), \( E \), \( A \), \( f_1 \) and \( f_2 \) is obtained.

\[
\Delta T = \text{purelin}\{\tan \text{sig}(V \cdot w_{11} + P_1 \cdot w_{12} + E \cdot w_{13} + f_1 \cdot w_{14} \\
+ A \cdot w_{15} + P_2 \cdot w_{16} + f_2 \cdot w_{17} + \theta_1 \cdot w_{18} + \alpha_1)\} \tag{1}
\]

The \( \tan \text{sig} \) function is defined as:

\[
f(x) = \frac{2}{1 + \exp(-2y_i)} - 1 \tag{2}
\]

where \( y_i \) is an output of the \( i \) neuron of the hidden layer,
which is defined as in Equation 3:

\[
y_i = \sum_{j=1}^{3} W_{ji}p_{ji}^{\theta} \tag{3}
\]

where \( p_{ji} \) is a matrix composed of \( P_1, P_2, V, E, A, f_1 \) and \( f_2 \).

The \( \text{purelin} \) function is a pure linear function, which
is defined as:

\[
\text{purelin}(x) = x \tag{4}
\]

where the independent variable is the output of the neu-
ron of the hidden layer; and the dependent variable is the
output of neuron of the output layer.

The parameter values of this correction Equation 1
for the sensor equipped with a DTR503A radiation
shield are:

\[
\begin{pmatrix}
4.578 & 2.835 & -5.489 & -5.771 & 2.157 & 0.224 & 1.038 \\
-0.821 & -0.374 & 0.741 & 0.271 & -0.14 & -0.152 & 8.585 \\
1.035 & 0.744 & -1.42 & -0.065 & 0.781 & 0.347 & 0.375 \\
0.852 & 0.149 & -0.336 & -0.246 & -0.017 & 0.05 & -7.816 \\
5.505 & -0.191 & 0.247 & -0.134 & -0.164 & -0.082 & -0.009
\end{pmatrix},
\begin{pmatrix}
w_{11} \\
w_{12} \\
w_{13} \\
w_{14} \\
w_{15} \\
w_{16} \\
w_{17} \\
w_{18} \\
\alpha_1
\end{pmatrix}
\]

\[
\begin{pmatrix}
\theta_1 \\
\theta_2 \\
\theta_3 \\
\theta_4 \\
\theta_5 \\
\theta_6 \\
\theta_7
\end{pmatrix} =
\begin{pmatrix}
-0.015 \\
-0.41641 \\
-0.83578 \\
0.358
\end{pmatrix}
\]

\[
\begin{pmatrix}
an_k
\end{pmatrix} =
\begin{pmatrix}
5.358
\end{pmatrix}
\]
The parameter values of the correction Equation 1 for the sensor equipped with a DTR13 radiation shield are:

\[
\begin{pmatrix}
0.153 & -0.06 & 0.051 & -0.044 & -0.063 & -0.028 & 0.05 \\
6.625 & -0.209 & 0.167 & -0.117 & -0.207 & -0.08 & 0.115 \\
1.336 & 0.083 & -0.421 & 0.086 & -0.072 & -0.01 & -0.08 \\
-1.474 & -0.045 & 0.369 & -0.041 & 0.096 & 0.023 & 0.036 \\
-0.499 & -1.057 & -0.222 & 5.907 & 3.57 & -0.93 & -0.89
\end{pmatrix},\ w_{ki} = 1.696, -4.779, 9.087, 5.155, 0.002, 2.422, -2.091, 3.068, a_k = 1.438
\]

Temperature error can be obtained by substituting \(V, P_1, E, f_1, A, P_2\) and \(f_2\) into the correction Equation 1. The temperature data obtained by using these radiation shields then can be corrected. Many factors can affect the uncertainty of the temperature error corrections calculated by using the correction equation. It is difficult to analyse all the factors in the equation. Because the temperature error caused by the direct solar radiation, reflected radiation, long wave radiation, air density, and so on, is greater than the temperature error induced by other factors, including dust, precipitation, measurement system, and so on, we study the relatively significant factors first. In follow-up research work, we will add these secondary factors into the correction equation to make the correction model more in line with the actual physical environment and further improve the accuracy of the temperature data. Although this correction Equation 1 is especially designed for the temperature sensor equipped with a DTR503A or a DTR13 radiation shield, the temperature error-correction method can be used on a variety of shields and sensors.

3 | EXPERIMENTAL STUDY

To verify the accuracy of this correction method, several field observation experiments were implemented on clear days. The proportion of clouds on these clear days was < 30%. The direct solar radiation intensity on these clear days can rise to 800 W·m\(^{-2}\). Four calibrated platinum resistance thermometers were installed in a DTR503A radiation shield, a DTR13 radiation shield, a 43502 aspirated radiation shield and a 076B aspirated radiation shield, respectively. In addition, we designed and manufactured a new multichannel thermometer circuit that can achieve up to 1–10 PPM repeatability under a typical outdoor environment. With a 0.05 PPM·K\(^{-1}\) low TCR reference resistor, electronics noise on the order of 1 mK and repeatability in the order of ≤ 5 mK have been observed with this circuit. The four thin-film platinum thermometers were calibrated by a comparison method, together with the new multichannel thermometer circuit. Calibration was performed using a high-precision SPRT connected to a 1595A super-thermometer as the reference sensor. The SPRT was calibrated using several fixed-point cells, according to the International Temperature Scale of 1990 (ITS-90). The expanded uncertainty associated with the resistance bridge (super-thermometer) calibration is 0.00008 Ω at a 95% confidence level. The uncertainty of calibration of the SPRT at 0°C is ±4 mK, expressed at a confidence level of 95%. The temperature stabilities and uniformity of the bath are ±5 and ±5 mK, respectively. Using the described equipment, four thermometers were calibrated with an uncertainty of 14 mK, expressed at a confidence level of 95%. These sensors were mounted onto a frame over grass. The airflow and the solar radiation are the main factors of the temperature error. Hence, it is necessary to measure air velocity and solar radiation intensity accurately. A CMP21 pyranometer and a 03002 wind sentry were adopted. These instruments are shown in Figure 6.

The flowing air is beneficial for the reduction of temperature error by promoting the diffusion of radiant heat. Because the flowing air can facilitate the diffusion of radiant heat, the temperature error can be reduced with the increase of air velocity through the shield. Because the aspirated radiation shield can provide a high air velocity, it has been used widely in weather stations. A sensor inside an aspirated shield usually serves as a temperature reference. R. M. Young Co. manufactured a 43502 aspirated shield with a high forced air velocity (5–11 m·s\(^{-1}\)). Met One Co. designed a 076B aspirated radiation shield with approximately 5 m·s\(^{-1}\) forced air velocity. By using an aspirated shield, error in the measurement of environmental air temperature can be reduced to 0.03°C. Therefore, during experiments, a
sensor inside a 076B aspirated shield and a sensor inside a 43502 aspirated shield were used as temperature references. Because the forced ventilation radiation shield does not block radiation completely, there will be still a certain temperature error present. In other words, the temperatures measured using the forced ventilation radiation shield may be higher than the real air temperature during the daytime. The greater the difference between the temperatures measured using the forced ventilation shield and the environmental air temperature, the greater the temperature error. Therefore, the lower of the temperatures measured when using two aspirated shields served as a reference during the experiments.

4 | VALIDATION OF THE TEMPERATURE ERROR-CORRECTION METHOD

4.1 | Measurement of and assumptions about environmental parameters

A CMP 21 pyranometer was used to observe the solar radiation intensity. A 03002 wind sentry was used to observe the air velocity. The altitude of the Nanjing Meteorological Observation Center is 22 masl. Once the time and location of the experiments are determined, the sun elevation angle and azimuth angle are determined. Because the sun elevation angle and azimuth angle are one-to-one correspondence, only the sun elevation angle is introduced in this correction equation.

The upwelling long wave radiation consists of the emitted long wave radiation from the underlying surface and the reflected downwelling long wave radiation:

\[ I_{l,0}^* = \varepsilon_g \sigma T_g^4 + \frac{1}{C_0/C_1} I_{l,0}^* \]

where \( T_g \) is the temperature of the underlying surface; and \( \varepsilon_g \) is the emissivity of the underlying surface.

Because \( I_{l,0}^* \) is much smaller than \( I_{l,0} \), Equation 5 can be simplified as:

\[ I_{l,0}^* = \varepsilon_g \sigma T_g^4 \]
We assumed the underlying surface to be a grey body. The emissivity of the underlying surface is 0.95. Equation 6 can be expressed as:

$$I_{1,0} = 0.95\sigma T_g^4$$  \hspace{1cm} (7)

Because the surface temperature fluctuates around 5°C during the experiments, the upwelling long wave radiation intensity is assumed to be 320 W·m⁻². Because the underlying surface is grassland during the experiments, and because the reflectivity of grassland ranges from 0.15 to 0.25, the reflectivity of the underlying surface is assumed to be 0.2. Since the instruments need regular cleaning and maintenance to reduce the effect of weathering on the albedos, the coating-reflecting ratio of the shield $f_2$ is assumed to be 0.87. The air velocity and solar radiation intensity observation results are shown in Figure 7.

### 4.2 Comparison between the temperature error given by the experiments and the correction equation

To verify the temperature error-correction method, comparisons between the temperature error calculated using the correction Equation 1 and the temperature error obtained by the experiments were performed. The calculated temperature errors were obtained by substituting $V$, $P_1$, $E$, $f_1$, $A$, $P_2$ and $f_2$ into the correction Equation 1. The temperature error determined by the experiment is the temperature measured using the sensor minus the temperature reference. Therefore, the temperature error
given by the experiment can be obtained with the help of the temperature reference. The temperature errors calculated using the correction Equation 1 and the temperature errors obtained through the observation experiments for the DTR503A and DTR13 shields are shown in Figure 8.

As shown, the measured temperature error results from the experiments and the calculated temperature error results from the correction Equation 1 are consistent with each other. To evaluate the accuracy of this temperature error-correction method, a root mean square error (RMSE) and a mean absolute error (MAE) are used:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - y_i)^2} \quad (8)$$

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^{n} |x_i - y_i| \quad (9)$$

where $x_i, y_i$ and $n$ are the temperature error provided by the correction method, the temperature error provided by the experiments and the total number of samples, respectively.

From Equations 8 and 9, the RMSE and MAE between the calculated temperature errors from the correction Equation 1 and the measured temperature errors from the experiments are listed in Table 2.

The temperature error is mainly caused by various radiations, including the direct solar radiation, the upwelling long wave radiation and the reflected solar radiation. In addition, because the degree of the radiant heat pollution is closely related to the coating reflecting ratio of the shield and the direction of the solar radiation, the coating reflecting ratio of the shield and the sun elevation angle are important factors. Because the heat dissipation potential of the air is closely related to air density and airflow velocity, the altitude and airflow velocity have a significant influence on the temperature error. As shown in Table 2, the RMSE and MAE results are much smaller than the temperature error for a temperature sensor installed in a DTR503A shield or a DTR13 shield. Because the RMSE and MAE results are both $< 0.05^\circ C$, this method may reduce the error of the temperature data to $0.05^\circ C$.

Nakamura and Mahrt (2005) proposed a correction method (Nakamura’s method) based on empirical equations; Cheng et al. (2014) proposed an improved correction method (Cheng’s method) based on Nakamura’s method. Jérémy et al. (2019) proposed a measurement equation based on a semi-empirical model. For low-response-time shelters, their results reduce the RMSE by about 15% ($0.07 K$) on average when compared with both Nakamura’s and Cheng’s methods. However, the error reduction ratio given by our method is approximately 90% on average.

### Table 2

| Shield   | RMSE ($^\circ C$) | MAE ($^\circ C$) |
|----------|-------------------|-----------------|
| DTR503A  | 0.043             | 0.038           |
| DTR13    | 0.049             | 0.044           |

5 | CONCLUSIONS AND FUTURE WORK

The paper proposed a temperature error-correction method. First, the computational fluid dynamics (CFD) method was used to quantify the temperature errors accurately. A neural network algorithm was then adopted to obtain a general temperature error-correction equation by fitting these temperature errors. Finally, to validate the correction equation, the corresponding field observation experiments were performed. The main conclusions and future work are as follows:

- The root mean square error (RMSE) and mean absolute error (MAE) results indicated that the temperature data are expected to reduce the temperature error to $0.05^\circ C$ with the support of the described temperature error-correction method. If the environmental factors corresponding to the temperature data can be quantified accurately, the factors influencing the temperature error can be added to the correction method continuously. The correction accuracy of this correction method may be further improved. The corrected temperature data may be used in climate change research and other fields.

- Due to the influence of solar radiation, the measured temperature is higher than the free-air temperature during the daytime. Because the temperature errors induced by long wave radiation during the night-time are much lower than the temperature errors caused by solar radiation during clear days, we first studied the relatively large temperature errors during the daytime. To improve the accuracy of the correction method, we will study how to reduce the temperature error during the night-time in future.
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ENDNOTES
1 See https://www.ipcc.ch/report/ar5/wg3/.
2 See https://www.ipcc.ch/sr15/.

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